Jos. W. Bursley

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INTERNATIONAL LIBRARY OF TECHNOLOGY

A SERIES OF TEXTBOOKS FOR PERSONS ENGAGED IN THE ENGINEERING PROFESSIONS AND TRADES OR FOR THOSE WHO DESIRE INFORMATION CONCERNING THEM. FULLY ILLUSTRATED AND CONTAINING NUMEROUS PRACTICAL EXAMPLES AND THEIR SOLUTIONS

DESIGN OF ALTERNATING-CURRENT APPARATUS
ELECTRIC TRANSMISSION
LINE CONSTRUCTION
SWITCHBOARDS AND SWITCHBOARD APPLIANCES
POWER TRANSFORMATION AND MEASUREMENT

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PREFACE

The International Library of Technology is the outgrowth of a large and increasing demand that has arisen for the Reference Libraries of the International Correspondence Schools on the part of those who are not students of the Schools. As the volumes composing this Library are all printed from the same plates used in printing the Reference Libraries above mentioned, a few words are necessary regarding the scope and purpose of the instruction imparted to the students of—and the class of students taught by—these Schools, in order to afford a clear understanding of their salient and unique features.

The only requirement for admission to any of the courses offered by the International Correspondence Schools, is that the applicant shall be able to read the English language and to write it sufficiently well to make his written answers to the questions asked him intelligible. Each course is complete in itself, and no textbooks are required other than those prepared by the Schools for the particular course selected. The students themselves are from every class, trade, and profession and from every country; they are, almost without exception, busily engaged in some vocation, and can spare but little time for study, and that usually outside of their regular working hours. The information desired is such as can be immediately applied in practice, so that the student may be enabled to exchange his present vocation for a more congenial one, or to rise to a higher level in the one he now pursues. Furthermore, he wishes to obtain a good working knowledge of the subjects treated in the shortest time and in the most direct manner possible.

In meeting these requirements, we have produced a set of books that in many respects, and particularly in the general plan followed, are absolutely unique. In the majority of subjects treated the knowledge of mathematics required is limited to the simplest principles of arithmetic and mensuration, and in no case is any greater knowledge of mathematics needed than the simplest elementary principles of algebra, geometry, and trigonometry, with a thorough, practical acquaintance with the use of the logarithmic table. To effect this result, derivations of rules and formulas are omitted, but thorough and complete instructions are given regarding how, when, and under what circumstances any particular rule, formula, or process should be applied; and whenever possible one or more examples, such as would be likely to arise in actual practice—together with their solutions—are given to illustrate and explain its application.

In preparing these textbooks, it has been our constant endeavor to view the matter from the student's standpoint, and to try and anticipate everything that would cause him trouble. The utmost pains have been taken to avoid and correct any and all ambiguous expressions—both those due to faulty rhetoric and those due to insufficiency of statement or explanation. As the best way to make a statement, explanation, or description clear is to give a picture or a diagram in connection with it, illustrations have been used almost without limit. The illustrations have in all cases been adapted to the requirements of the text, and projections and sections or outline, partially shaded, or full-shaded perspectives have been used, according to which will best produce the desired results. Half-tones have been used rather sparingly, except in those cases where the general effect is desired rather than the actual details.

It is obvious that books prepared along the lines mentioned must not only be clear and concise beyond anything heretofore attempted, but they must also possess unequaled value for reference purposes. They not only give the maximum of information in a minimum space, but this information is so ingeniously arranged and correlated, and the

indexes are so full and complete, that it can at once be made available to the reader. The numerous examples and explanatory remarks, together with the absence of long demonstrations and abstruse mathematical calculations, are of great assistance in helping one to select the proper formula, method, or process and in teaching him how and when it should be used.

The first portion of this volume contains an exceptionally distinct and intelligible treatise on the complex problems relating to the design of alternating-current apparatus. The correct proportions and relative location of the different parts of the machines are clearly set forth and illustrated by numerous figures showing the details of the construction. The design of alternators, motors, and transformers is fully discussed. The various systems of transmitting electrical energy, and the methods used in calculating the size of wires, and installing the wires for overhead and underground transmission systems, are described in great detail, and complete wire data tables are furnished. The treatment of switchboards in this volume is very complete and is superior to anything yet published. The recent styles of oil switches, circuit-breakers, measuring instruments, etc. are fully explained and illustrated, and their location indicated on the switchboard diagrams. Under the heading Power Transformation and Measurement, a very clear treatise is given of the installation of transformers and substations and the methods of power measurements.

The method of numbering the pages, cuts, articles, etc. is such that each subject or part, when the subject is divided into two or more parts, is complete in itself; hence, in order to make the index intelligible, it was necessary to give each subject or part a number. This number is placed at the top of each page, on the headline, opposite the page number; and to distinguish it from the page number it is preceded by the printer's section mark (§). Consequently, a reference such as § 16, page 26, will be readily found by looking along the inside edges of the headlines until § 16 is found, and then through § 16 until page 26 is found.

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CONTENTS

DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 1)

ALTERNATORS

1. The design of alternators is in many respects similar to that of multipolar continuous-current machines, many of the parts being very similar. For example, the method of calculating the field ampere-turns, and the design of the field in general, is much the same in these two classes of machines. A great many of the mechanical details are also similar, and much of what has already been given as applying to continuous-current machines applies also to alternators.

2. Some of the calculations connected with the design of alternators are, however, not so easily made as for direct-current machines, and the production of a good design depends largely on the skill and previous experience of the designer. For example, there is a large variety of armature windings to select from, and the designer has to decide which winding is best adapted for the work that the alternator has to do. Such calculations as the estimation of armature inductance, armature reaction, etc. are difficult to make without having had previous experience with machines of the same type as that being designed. The quantities are, in general, easily determined after the machine has

been built, but their previous calculation is difficult. For this reason the design of alternators is, on the whole, more empirical than that of continuous-current machines. There is also a greater choice as to the mechanical arrangement of the different parts, since either the field or armature may be the revolving member.

LIMITATION OF OUTPUT

3. The output of an alternator, like that of a direct-current machine, may be limited by the heating of the armature. This heating is due to two causes, namely, the $I^2 R$ loss in the armature conductors, and the core loss due to the hysteresis and eddy-current losses in the mass of iron constituting the armature core. Both these losses appear in the form of heat, and cause the armature as a whole to rise in temperature. Since the maximum temperature at which an armature can be run with safety is limited by the temperature to which the insulating material may be subjected continuously without injury, it follows that this heating effect is an important factor, limiting the output of the machine.

4. The output may in some cases be limited by self-induction and armature reaction. If the inductance of the armature is very high, a considerable part of the E. M. F. generated may be used to force the current through the armature itself, thus reducing at the terminals of the machine the E. M. F. available for use in the external circuit. In other words, if an alternator having an armature with high self-inductance is run with a constant field excitation, the voltage between the collector rings will fall off as the load is applied. Most alternators have to be built under a certain guarantee as to **voltage regulation.** By the voltage regulation is meant the percentage that the voltage rises when the full load is thrown off an alternator. That is, suppose an alternator, when carrying full load, generates 2,000 volts, and when the load is thrown off the voltage rises to 2,100, the field excitation and speed remaining the same. The increase is 100 volts, or 5 per cent. of the full-

load voltage, and the regulation would be 5 per cent ; the percentage always refers to full-load voltage, because full load is taken as the normal operating condition of the machine.

5. In most of large slow-speed alternators of the revolving field type the ventilation is so good that the full-load current can be delivered with a rise in temperature well within the safe working limit. If, however, these machines are not carefully designed they may not give the voltage regulation required. The voltage may drop more than the allowable amount when full load is applied because of the armature reaction and self-induction. In such cases, therefore, the output that the machine can deliver without exceeding the specified limit of voltage regulation may be limited by the armature reaction and self-induction, and not by heating. For certain classes of work close regulation is very important, and in many cases the regulation becomes a more important factor in the design, so far as limitation of output is concerned, than heating.

As pointed out later, the regulation depends a great deal on the character of the load that the machine carries. The regulation might be very good on a non-inductive load and so poor on an inductive load that the machine could not be made to maintain its voltage even with the fields excited to the fullest extent. A statement of the regulation should always include a statement of the character of the load for which the regulation is given, i. e. whether non-inductive or inductive, and, if the latter, the power factor.

6. In high-speed alternators, such as those driven by belts or by steam turbines, the armature presents comparatively small surface for the dissipation of heat, and unless special means are provided for ventilation, the heating effect will be an important factor in determining the allowable output. In direct-current machines, sparking at the commutator often limits the output, but obviously this does not apply to alternators, because no commutator is used, except in some cases as an auxiliary part in connection with the field-exciting circuit. However, while armature reaction

cannot cause sparking in an alternator it has a decided influence on the voltage regulation, and its effects must be carefully considered.

HEATING OF ALTERNATOR ARMATURES

7. The final temperature that an armature attains when carrying its normal load depends not only on the actual amount of energy wasted in the armature, and that appears in the form of heat, but also on the readiness with which the armature can get rid of this heat to the surrounding air. The armature will always keep on increasing in temperature until it reaches a point where it radiates the heat to the air as fast as it is generated. The rise in temperature necessary to accomplish this will evidently depend largely on the construction of the armature. A well-ventilated armature will get rid of more heat per degree rise than a poorly ventilated one; hence, every effort should be made, in designing an armature, to arrange it so that the air can circulate freely around the core and conductors. This is best done by mounting the armature disks on an open spider, and providing air ducts through the iron core, which allow a circulation of air when the machine is running. By adopting this construction, makers have been able to reduce the size of armature for a given output compared with the size required for the same output when the older style, with surface windings and unventilated core, was used. The heat loss due to hysteresis and eddy currents in the core is about the same, whether the machine is loaded or not. Suppose an alternator to be run on open circuit with its field fully excited. There will be no loss in the armature conductors, because the machine is furnishing no current. The mass of iron in the core is, however, revolving through a magnetic field, and there will consequently be a hysteresis loss in the iron, and eddy currents will be set up in the armature disks. These will cause the armature to heat up until the rise in temperature is sufficient to radiate these core losses. When the machine is loaded,

we have, in addition to the above, the heat loss in the conductors due to the current that is now flowing. The result is that the armature increases further in temperature until it reaches a final temperature that allows the armature to get rid of all the heat generated in it. If the armature is overloaded, the I^2R loss becomes excessive, and a point is soon reached where it becomes unsafe to load the machine further.

8. What was said regarding the safe heating limit of the insulating materials used in the construction of continuous-current armatures applies also to armatures for alternators. There is no good reason why an alternator armature should be worked at a higher temperature than that of a direct-current machine, although in many alternators, especially some of the older styles, the limit is much higher. In modern machines, however, the rise of temperature is very little, if any, higher than in continuous-current machines of corresponding output and speed. The final temperature when running fully loaded should not exceed 40° to 50° C. above that of the surrounding air.

9. The total temperature that the armature attains when fully loaded depends on the temperature of the surrounding air. It is not safe to count on less than 20° C. for the average temperature of the surrounding air, because the air in dynamo rooms in summer often goes far above this. A fair rise in temperature may therefore be taken as from 70° to 80° F., or from 40° to 50° C. These are the ordinary values used in rating machines, and if an alternator will deliver its full load continuously, with a rise in temperature not exceeding the above, it should be perfectly safe, as far as danger from overheating goes. The rise in temperature of the field coils is generally not quite as high as that of the armature, but it must be remembered that while the outside layers of the coils may be comparatively cool, the inner turns may be quite hot, and it is the greatest temperature that any part of the coils attains that must be taken into account.

RELATION BETWEEN I^2R LOSS AND OUTPUT

10. The I^2R loss in an armature at full load usually bears a certain ratio to the output of the machine. An alternator with an excessive I^2R loss in the armature conductors would have a low efficiency. It is therefore important that the armature be so designed that the heat loss in the winding shall not exceed a certain proportionate amount of the total output. This loss can be decreased by decreasing the resistance of the armature winding. The resistance can be decreased by either shortening the length of wire on

I^2R loss in % of output.

Curve showing relation between armature I^2R loss & output of alternator.

FIG. 1

the armature or by increasing its cross-section. A certain length of active conductor is necessary for the generation of the E. M. F.; hence, to keep down the I^2R loss, we must use an armature conductor of large cross-section. The size of conductor, if increased too much, calls for a large armature for its accommodation, and the machine is thus rendered bulky and expensive. All that can be done, therefore, is to design the armature winding so that the heat loss will be as small as is consistent with economy of construction. Older types of alternators had a large armature

I^2R loss, but the curve drawn in Fig. 1 may be taken as giving the average loss for ordinary alternators. The abscissas of this curve give the output in kilowatts, and the ordinates, the I^2R loss in per cent. of the output. It will be understood that the loss in individual machines might vary somewhat from the values shown, but the curve shows the average relation for machines where the I^2R armature loss is not excessive. It will be noticed that this loss is a much larger percentage for small machines than for large ones. For machines over 100 K. W., the percentage loss does not decrease much with increased output.

CORE LOSSES

11. The core losses have already been mentioned as one of the causes producing heat in the armature. These losses are present also in continuous-current armatures, but their effects are usually much less than in alternators. In some alternators the core losses are nearly if not quite as great as the I^2R loss, and consequently the no-load rise in temperature may be considerable.

HYSTERESIS LOSS

12. The nature of this loss has already been explained in connection with the design of direct-current machines and the method of calculating it pointed out, so that it will not be necessary to dwell further on it here. The curves shown in Fig. 2 will be found useful for calculating the hysteresis loss in alternating-current apparatus. Curve A shows the relation between the maximum magnetic density and the watts lost per cubic inch per 100 cycles for a good quality of soft transformer iron Curve B shows the loss for ordinary armature iron of good quality. In order to obtain the total hysteresis loss for a given mass of iron, multiply the value given by the curve corresponding to the maximum density at which the iron is worked, by the volume in cubic inches and the frequency and divide the result by 100.

EXAMPLE.—The armature core of an alternator having 12 poles and running at a speed of 600 revolutions per minute is worked at a maximum magnetic density of 20,000 lines per square inch. If the volume of the core is 2,000 cubic inches, how many watts will be wasted in hysteresis?

Magnetic density $\mathfrak{B}$ *(lines per sq. inch)*

FIG. 2

SOLUTION.—If the machine runs at 600 rev. per min. and has 12 poles, the frequency of the magnetic cycles in the armature core must be $\frac{12}{2} \times \frac{600}{60}$, or 60 cycles per second.

By referring to curve *B*, Fig. 2, we find the loss per cubic inch per 100 cycles corresponding to a density of 20,000 to be about .22 watt. Hence, the total loss will be

$$W_H = \frac{.22 \times 2{,}000 \times 60}{100} = 264 \text{ watts.} \quad \text{Ans.}$$

13. The hysteresis loss, other things being equal, increases directly with the frequency. It is on this account that this loss is usually greater in alternator armatures than in those used for direct-current machines, because the frequency of the former is usually much higher than that of the latter. Special care should therefore be taken in the selection of core iron for all kinds of alternating-current apparatus. It will also be noticed that the hysteresis loss, being proportional to the 1.6th power of the magnetic density, will increase quite rapidly as the density is increased. It follows, therefore, that the core densities used should be low, otherwise the hysteresis loss may become excessive. It is usual to employ lower core densities in alternating-current machines than in continuous-current machines, because the frequency is usually fixed by the conditions under which the machine has to work, and a low density is therefore necessary to keep down the hysteresis loss.

EDDY-CURRENT LOSS

14. The other core loss mentioned above, namely that due to eddy currents, is not usually very large, provided proper care is taken in building up the armature core. This loss is due to local currents circulating in the armature disks, and the eddy-current loss is really an $I^2 R$ loss caused by the resistance offered to these currents by the iron constituting the core. If the core is thoroughly laminated, the paths in which these currents flow are so split up that the currents are confined to the individual armature disks. This keeps down the volume of the eddy currents, and if the disks are well insulated and made of thin iron, the eddy-current loss may be made very small. Anything that makes electrical connection between the disks may largely increase this loss. For example, filing out the slots, or burring over the disks, or passing uninsulated clamping bolts through the core may result in an increased loss. It

is well, therefore, to avoid filing or milling the slots unless it is absolutely necessary to render them smooth enough to receive the insulating troughs and armature conductors. The eddy-current loss is proportional to the square of the frequency, other things being equal; hence it is usually greater in alternators than in direct-current machines. If proper precautions are taken in building up the core, the eddy-current loss should be small compared with the $I^2 R$ and hysteresis losses. It is difficult to calculate this loss beforehand, on account of the large variations caused in it by defects in the insulation of the core disks from each other.

RADIATING SURFACE OF ARMATURE

15. The armature has to present sufficient radiating surface to get rid of the heat dissipated without a rise in temperature exceeding, say, 40° or 50° C. This means that the size of the armature will, for a given output and given amount of loss, depend on the ease with which it can radiate the heat. The number of watts that an armature can radiate per square inch of surface per degree rise in temperature varies greatly with the style and construction of the armature and the peripheral speed at which the armature is run, so that it is not possible to give any values for this radiation constant that will be applicable to all styles of armatures. A well-ventilated iron-clad alternator armature should be able to radiate from .04 to .06 watt per square inch of cylindrical surface (circumference of iron core × length parallel to shaft) per degree rise. These values are for machines running at peripheral speeds of from 4,000 to 5,000 feet per minute; if the peripheral speed were higher, the watts radiated per square inch per degree rise would be correspondingly increased. This means, then, assuming 40° C. to be the allowable rise, that a well-ventilated armature of the above type should be capable of radiating from 1.6 to 2.8 watts per square inch of cylindrical

surface. In well-designed alternators, the sum of the hysteresis and eddy-current losses will not, as a rule, be greater than the $I^2 R$ loss, so that we will, in general, be safe in assuming that an allowance of from .8 to 1.4 watt $I^2 R$ loss for each square inch of surface will give an armature of sufficient radiating surface to keep the total rise in temperature due to all the losses from exceeding 40° C. This will give a preliminary value for the surface of the armature on which to base subsequent calculations, bearing in mind that the dimensions so obtained are not necessarily final, and may be modified as the design is worked out further, provided always that the armature is made of such dimensions that it will be able to get rid of the heat generated. Machines have been built in which the surface per watt is less than that given above, but it will usually be found that such machines run very hot when fully loaded unless their peripheral speed is very high or their ventilation exceptionally good. Alternator armatures of the iron-clad type can usually be constructed so as to secure good ventilation, especially if they are of fairly large diameter, so there should be no difficulty in radiating the amount of heat just given. The watts per square inch as given are referred to the outside cylindrical surface; of course, the ends of the core, and to a certain extent the inside also, help to radiate the heat, but it is more convenient for purposes of calculation to refer the watts radiated per square inch to the outside core surface rather than to the surface of the armature as a whole.

ARMATURE REACTION

16. Armature reaction, in connection with alternators, has already been mentioned in a general way, and it now remains to be seen just how it affects the action of a machine when loaded. The matter of armature reaction plays an important part in the design of continuous-current machines, as has already been shown in the section on the design of

such dynamos. If the armature of a continuous-current machine is capable of overpowering the field, bad sparking will result at the commutator. This, however, cannot occur in the case of an alternator, and the only bad effect that the reaction can have is to cause a weakening and distortion of the field, with a consequent reduction of the voltage generated in the armature.

17. Let *N*, Fig. 3, represent one of the north poles of an alternator, surrounded by its magnetizing coil *a*. The lines of force will flow into the armature from the pole piece, as indicated by the lines and arrowheads. We will consider the instant when the coil *c c'* has its opening directly under the pole, or when the center of the tooth *b* is opposite the center of the pole piece. If there is no self-induction present, the current flowing through the armature will be in phase with the E. M. F. generated; consequently, at the position shown in the figure, the current in the coil will be zero, because the coil is cutting no lines of force, and the E. M. F. generated is consequently zero. It follows, then, that under this particular set of conditions the armature coil has no disturbing effect on the lines of force set up by the field. The direction of rotation is indicated by the arrow, and a moment later the bundle of conductors in the slot *c* is under the center of the pole, as shown in Fig. 4. The current in the conductors will now be at its maximum value, because the E. M. F. generated is at its maximum. The current will be flowing down through the plane of the paper, and the bundle of conductors lying in

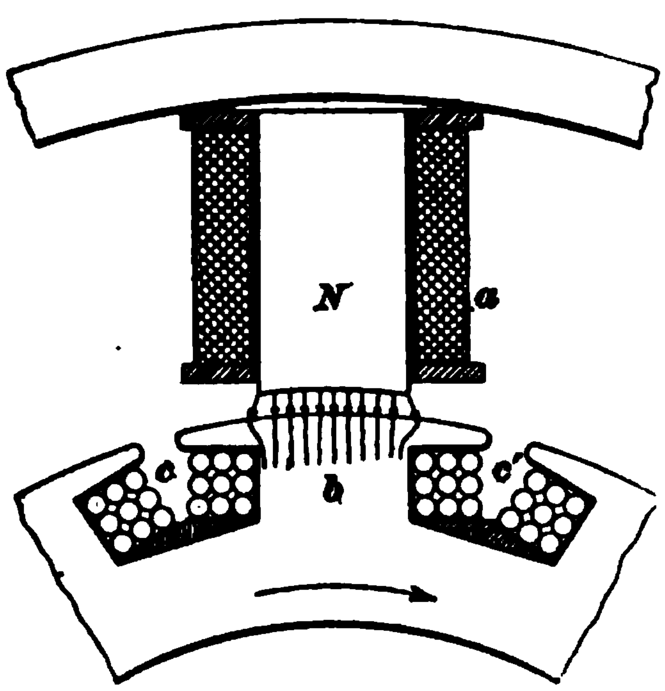


FIG. 3

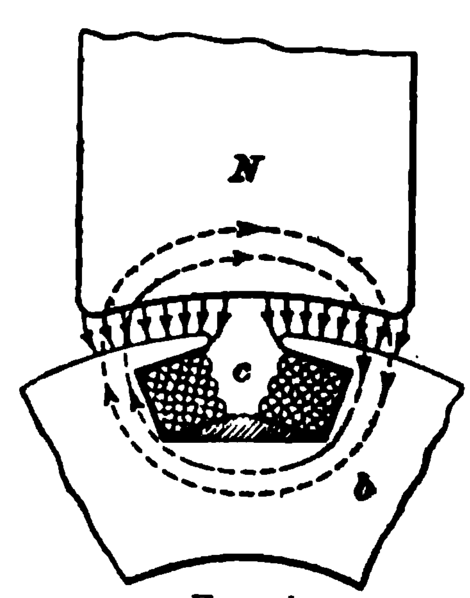


FIG. 4

the slot will tend to set up lines of force around themselves, as shown by the dotted lines, and in the direction shown by the arrowheads. It will be noticed that this field set up by the conductors tends to strengthen the right-hand side of the pole and weaken the left-hand side by a like amount. The resultant effect is therefore to crowd the field forwards in the direction of rotation, making it denser at the right-hand side, as shown in Fig. 5. It is therefore seen that in this respect the effect of armature reaction is similar to the effect observed in direct-current machines; but in an alternator with coils, as shown in the figures, the effect on the field is not steady, but varies as the teeth move past the poles. The student should note that in this case the armature and load are assumed to have no self-induction, and also that the armature reaction tends only to change the distribution of the field and not to weaken it.

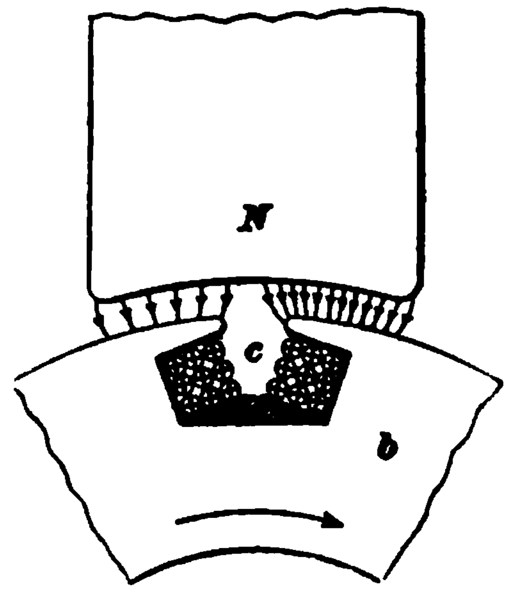


FIG. 5

18. Armatures always have more or less self-induction, especially if they are provided with heavily wound coils sunk in slots. The effect of this self-induction is, of course, to cause the current in the armature to lag behind the E. M. F. It is necessary, then, to see how this lagging of the current affects the reaction of the armature on the field. In this case the current in the coil does not die out at the same instant as the E. M. F., but persists in flowing after the E. M. F. has become zero. The current, instead of being zero when the tooth is under the pole, will then be flowing as shown in Fig. 6; that is, the current

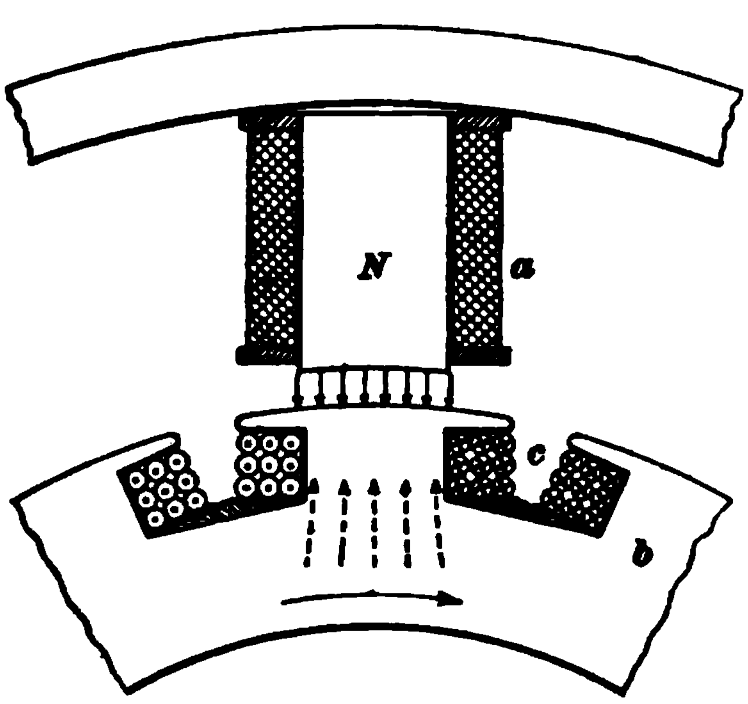


FIG. 6

in the conductors in slot *c* persists in flowing, as shown in Fig. 5, after the conductors have moved out from under the pole piece. This current flowing in the armature coil will set up lines of force through the coil in the direction shown by the dotted arrows, i. e., directly opposed to the original field. The armature reaction, therefore, not only tends to distort the field, but also tends to weaken it when there is a lagging of the armature current due to self-induction in the armature or external load. This reaction of the armature on the field would of course cause a falling off in the voltage of the machine if the field magnets were not strengthened to counterbalance its effects. It is instructive to note here that if it were practicable to have a condenser in connection with the armature, the current could be made to lead the E. M. F., and the armature reaction would then tend to magnetize the field instead of demagnetize it.

19. It is seen from the above that in alternator armatures in which there is an appreciable amount of self-induction present, we have two effects similar to those produced by the cross ampere-turns and back ampere-turns of a continuous-current armature, the former tending to distort the field, and the latter acting directly against it and tending to weaken it. The bad effects of this reaction can be reduced, as in the case of direct-current machines, by lengthening the air gap. The actual amount of distortion or demagnetization is not easily calculated, as it evidently changes with the changes in the current, and also depends on the armature inductance, which is itself difficult to estimate without data from machines of the same type. The distribution of the field can be determined after the machine has once been built, and unless the air gap is very short, the distortion is not sufficient to badly affect the working of the machine.

20. One effect of armature reaction is sometimes taken advantage of in designing armature windings, namely, the crowding together of the lines to one side of the pole piece,

This practically makes the effective width of the pole face less and allows the use of coils on the armature with an opening somewhat less than the width of the pole face, without danger of the E. M. F.'s in the different turns of the coil opposing each other.

ARMATURE SELF-INDUCTION

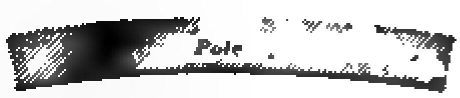
21. It has just been shown that self-induction is indirectly responsible for the demagnetization of the field, which in turn produces a falling off in voltage. Self-induction also calls for a considerable E. M. F. to force the current through the armature, and this causes a still further diminution in the E. M. F. obtained at the terminals. This drop in voltage has already been explained in the section on *Alternators*. A machine with high armature self-induction will not maintain a constant terminal pressure unless the field is strengthened as the load is applied, and such machines therefore require heavily compounded fields.

22. In general, armatures wound with a few heavy coils bedded in slots have a high self-induction, because the coils are able to set up a large number of lines around themselves when a current flows through the armature. Machines with this style of armature winding usually give an E. M. F. curve that is more or less peaked and irregular. Such windings are easily applied to the armature, and being of very simple construction, they necessitate very few crossings of the coils at the ends where the coils project from the slots. They are, therefore, easy to insulate for high voltages, and are extensively used on alternators for operating incandescent lights.

23. The inductance depends on the way in which the coils are arranged in the slots. Fig. 7 (*a*) shows a cross-section of a slot containing a heavy coil of 40 turns. When current is passed through the coil, a magnetic field is set up

that encircles the coil as indicated by the dotted lines. The self-induced E. M. F. will depend on the strength of this field and on the number of turns with which the field is linked. The strength of field depends on the current, the number of turns, and the reluctance of the magnetic path surrounding the turns. If the reluctance is a constant quantity, it is evident that the self-induced E. M. F. for a given current will increase as the square of the number of

(a)



(b)

Fig. 7

turns per coil or conductors per slot. Such being the case, the inductance could be decreased by splitting up the single coil into two or more coils placed in separate slots, thus reducing the number of conductors per slot. For example, suppose an armature has 6 coils of 40 turns each, and that the inductance of each coil is .02 henry. The coils are supposed to be connected in series, so that the total inductance of the armature will be $6 \times .02 = .12$ henry.

Suppose, now, the winding is split up into 12 coils of 20 turns each, the shape and arrangement of the coils being kept the same. We will then have the same total number of turns as before, but will have half as many turns per coil or half as many conductors per slot. The inductance of each coil will therefore be one-fourth of what it was before, because the inductance will decrease as the square of the number of turns per coil. The inductance per coil will then be $\frac{1}{4} \times .02 = .005$ henry, and the total inductance will be $.005 \times 12 = .06$ henry, or one-half of what it was in the former case. In order, then, to decrease the inductance of an armature, the number of turns per coil must be decreased, or, what amounts to the same thing, the number of conductors per slot must be decreased.

In the preceding example, it has been assumed that the reluctance of the path around the coil is the same for the heavy coil as for the light coil. This, however, is not the case in practice, and the reduction of inductance by subdividing the winding is not as great as the theoretical example just given would indicate. In Fig. 7 (*a*), it will be noticed that the greater part of the reluctance of the magnetic path occurs at the air gaps around the top of the slots, as indicated at *a b*. With a wide shallow slot, the reluctance of the path *c d* between the sides of the slot is also larger. When the coil is split up, it is necessary to use narrower slots and teeth, as shown at (*b*), so that the air gap *a b* is made much shorter. Also, the slots being deep and narrow compared with (*a*), the reluctance between the sides of the slot itself is less. The result is that the decrease in the number of conductors per slot may be offset to a considerable extent by the decreased reluctance, so that the product of the flux times turns may not be reduced to nearly so great an extent as the decrease in the turns per coil would lead one to expect. With the narrower slots in (*b*), the higher tooth density tends to keep up the reluctance of the magnetic path, but saturated teeth are not used as much in alternators as in direct-current machines, and the tendency of making the slots narrower and deeper is, on the whole,

to reduce the reluctance of the path for the magnetic flux that is responsible for the setting up of the induced E. M. F.

While, therefore, the splitting up of the winding does not reduce the inductance in proportion to the square of the number of turns per coil, yet it does reduce it considerably, and for machines where low armature inductance and close voltage regulation are desired, the winding is usually split up in the manner described. This subdivision of the winding will be described more fully later.

24. Calculation of Armature Inductance.—Since the inductance of the armature coils depends on the reluctance of the magnetic path around the coils, it is evident that it will be influenced not only by the size and shape of the slots, but also by the position of the armature with regard to the field, and also by the length of the air gap between armature and field. For example, in Fig. 7 (*a*), when the bundle of conductors is under the poles, as shown, the inductance is a maximum because the iron pole face helps to carry the flux around the conductors. If the air gap were very short, it is evident that the reluctance of the path for the induced flux would be much less with the slot under the poles than when between the poles, because in the latter case the path between the tops of the teeth would be wholly through air. It is evident that with a long air gap there would be little difference in the inductance under the poles and between the poles. The inductance is therefore not constant, but varies with the position of the slots with regard to the pole pieces. It is also evident that the number of lines set up through a coil will be proportional to the length of the laminated core, i. e., the length parallel to the shaft, so that for an equal number of turns, short armatures have a lower inductance than long ones.

25. On account of the number of variable quantities that enter into the calculation of the inductance, it is not possible to lay down any rule that will apply to all sizes of slot, air gap, length of core, etc. Inductance calculations

are based on data obtained from tests of machines of similar type to the one being designed. Parshall * gives a number of tests made to determine the inductance of various armatures and shows that the field set up around a coil varies from 13 to 140 or 150 lines per ampere-turn per inch length of armature core. The latter high values are for armatures with a very short air gap and with the conductors under the poles in the position of maximum inductance. For fairly wide slots, and with the conductors in the position of minimum inductance between the poles, the value is from 15 to 20 lines per ampere-turn per inch length of core. For example, suppose an armature coil had 40 turns and that we take 20 lines per ampere-turn per inch length of core as a fair value for the field set up around the coil. Also, suppose that the armature core is 8 inches long. The flux through the coil will then be $20 \times 8 \times 40 = 6{,}400$ lines for a current of 1 ampere. We have

$$\frac{\Phi \times T}{10^8} = L$$

where Φ is the flux corresponding to a current of 1 ampere, T the number of turns, and L the inductance in henrys. Then, in this case,

$$L = \frac{6{,}400 \times 40}{10^8} = .00256 \text{ henry}$$

The probable value of the flux can usually be calculated from data obtained from tests on similar machines, and data of this kind is absolutely necessary if accurate estimates of inductance are to be made. The preceding example will, however, give the student an idea as to the elements on which the value of the inductance depends. If the inductance L is known, the armature reactance is easily obtained from the expression $2 \pi n L$, where n is the frequency. The voltage necessary to overcome the reactance is $2 \pi n L I$, where I is the current in the armature.

* "Electric Generators," Parshall and Hobart.

Alternators provided with armatures of low inductance give a much better E. M. F. regulation than those having high inductance, because the reaction on the field is not only less, but much less of the E. M. F. generated is used up in driving the current through the armature. In other words, such machines, if provided with a constant field excitation, will show only a moderate falling off in terminal voltage from no load to full load. On this account, it is quite common to find such machines built without any compound or series-winding on the fields, all the regulation necessary being accomplished by varying the current supplied to the field coils by the exciter. Such alternators give a smooth E. M. F. curve that approximates closely to the sine form, and alternators of this type are being used extensively for power-transmission purposes.

26. An excessive amount of armature inductance, and consequent damagnetizing armature reaction, has been used to make alternators regulate for constant current. In such machines the armature inductance is made very high, and a small air gap is used between the armature and field. If the current delivered by such a machine tends to increase by virtue of a lowering of the external resistance, the armature reaction on the field increases and the field is weakened. This cuts down the voltage generated, so that the voltage adjusts itself to changes in the load, and the current remains constant.

PERIPHERAL SPEED OF ALTERNATOR ARMATURES

27. Alternators have been built to run at peripheral speeds much higher than those used for continuous-current machines. This was the case in many of the older types of lighting machines running at a high frequency. Since the frequencies employed were high, the revolutions per minute of the armature also had to be high in order to avoid using a very large number of poles. This high speed of rotation usually resulted in high peripheral speeds also, because the

armature could not be made very small in diameter. Such machines often ran at peripheral speeds as high as 7,000 or 8,000 feet per minute. Modern revolving-field machines for direct connection to waterwheels often run 7,000 or 8,000 feet per minute, and steam turbine alternators from 12,000 to 15,000.

28. The frequency of a great many modern machines is lower than that formerly used, 60 or 25 cycles per second being standard values. The lowering of the frequency was accompanied by a lowering of the peripheral speed, and the peripheral speeds of revolving armature alternators compare favorably with those of multipolar direct-current machines of the same output. Peripheral speeds for belt-driven 60-cycle alternators may be taken from about 3,500 to 5,500 feet per minute. The peripheral speed of some of the larger direct-connected alternators may be even lower than this, just as the peripheral speed of multipolar direct-current generators is usually lower than that of belt-driven machines. Alternators of the inductor or revolving field construction can be run at higher peripheral speeds than those with a revolving armature on account of the mechanical construction of the revolving field or inductor being more substantial than that of a revolving armature.

ARMATURE WINDINGS

29. The foregoing articles have dealt with different subjects relating to the behavior of armatures. We will now take up those subjects that deal more particularly with their design. Some of the most important points in the design of an armature are the selection of the type of winding to be used for a given case, the method of connecting it up, and the means used for applying the winding to the armature. Alternator windings have already been dealt with to some extent in the section on *Alternators*, but the following articles are intended to bring out some points of difference between concentrated and distributed windings

that are necessary for the designing of armatures for alternators and fields for induction motors.

30. Alternator windings may be divided into two general classes, namely: (*a*) uni-coil or concentrated windings; (*b*) multi-coil or distributed windings. These may further be subdivided into (1) uni-coil single-phase windings; (2) multi-coil single-phase windings; (3) uni-coil polyphase windings; (4) multi-coil polyphase windings.

The uni-coil windings for single-phase, two-phase, and three-phase machines have been treated in the section on *Alternators*. We will presently examine single-phase multi-coil, or distributed windings, to see how the spreading out of the winding affects the voltage generated by the armature.

SINGLE-PHASE CONCENTRATED WINDING

31. A single-phase concentrated winding has only one slot or bunch of conductors under each pole; consequently, the conductors are practically all active at the same instant, and the maximum E. M. F. is obtained with a given length of active armature conductor. This E. M. F. is given by the formula

$$E = \frac{4.44\, \Phi\, T n}{10^8}$$

where T = number of turns connected in series on the armature;

Φ = total magnetic flux from one pole;

n = frequency;

E = E. M. F. generated in armature, or E. M. F. obtained between the collector rings at no-load.

Such windings have therefore the advantage of giving a high E. M. F. for a given length of conductor, but they have the disadvantage that they give rise to high armature self-induction and consequent falling off in terminal voltage when the machine is loaded. Also, the heating of the coils is likely to be greater than if they were spread out.

SINGLE-PHASE DISTRIBUTED WINDINGS

32. It has been shown that the self-induction can be reduced by splitting up the coils and distributing them over the armature. Such distribution is, however, always accompanied by a lowering of the E. M. F. generated, even though the total number of turns be kept the same. Suppose, for example, we have a single-phase armature with T turns, connected in series and arranged with only one slot or bunch of conductors under each pole. The E. M. F. generated will then be

$$E = \frac{4.44\ \Phi\ T n}{10^8}$$

Suppose, now, we spread the winding out so that there will be two sets of conductors or two slots for each pole, and

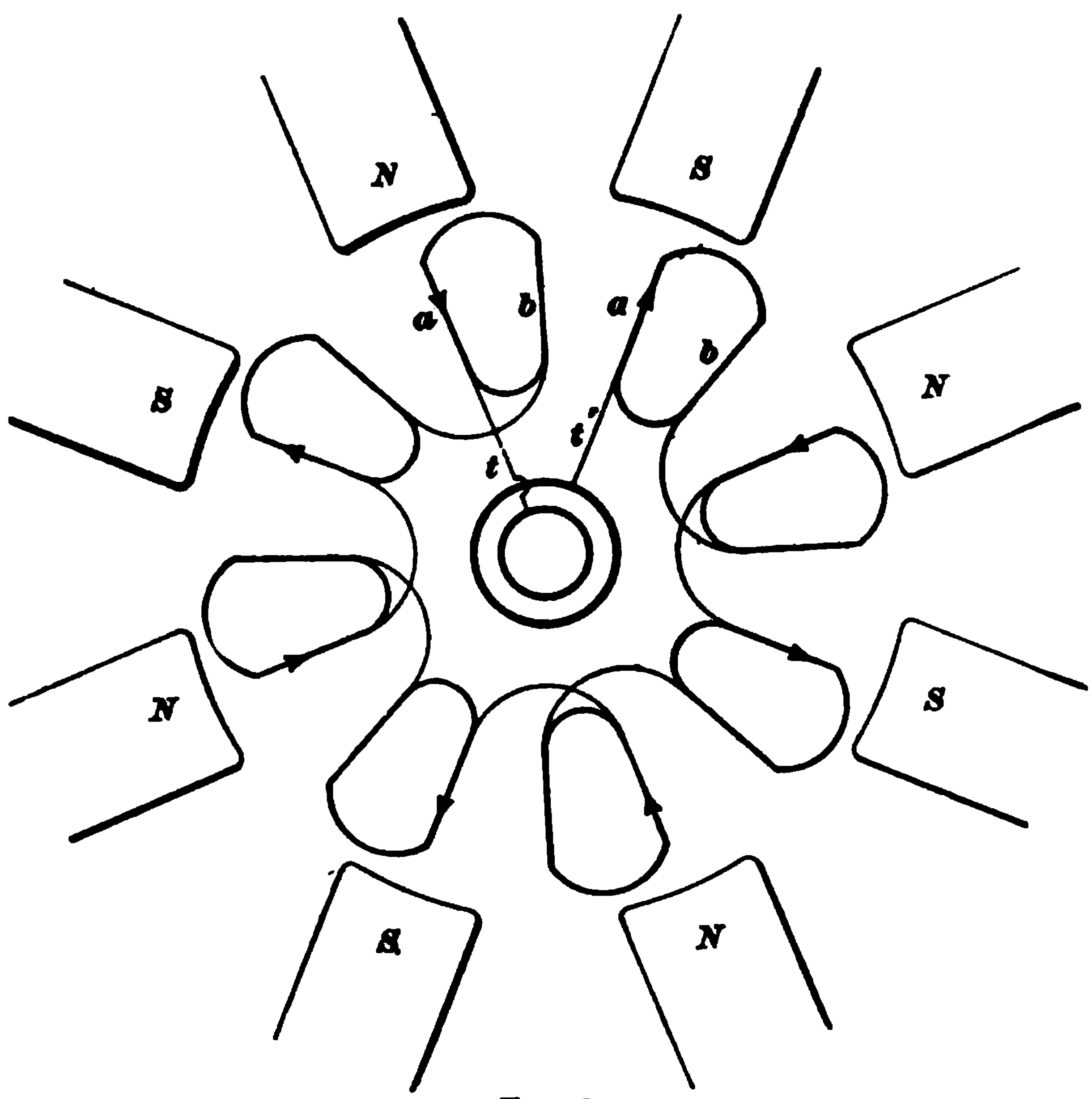


FIG. 8

distribute these slots equally around the armature. We will put half as many conductors as before in each slot, so that

the total number of conductors and turns will remain the same as before. This will give us a winding similar to that shown in Fig. 8. This shows an eight-pole single-phase winding with two slots per pole piece. By examining the figure, it is evident that with such an arrangement the conductors in slot *b* are, at the instant when they are directly between the poles, generating zero E. M. F., while those in *a* are generating the maximum E. M. F. The E. M. F. that will be obtained between the collector rings will be the sum of the two, as shown in Fig. 9. *O a* represents the E. M. F. generated in one set of conductors, while *O b* represents the E. M. F. generated in the other. These two E. M. F.'s will be equal, and will be given by the expression

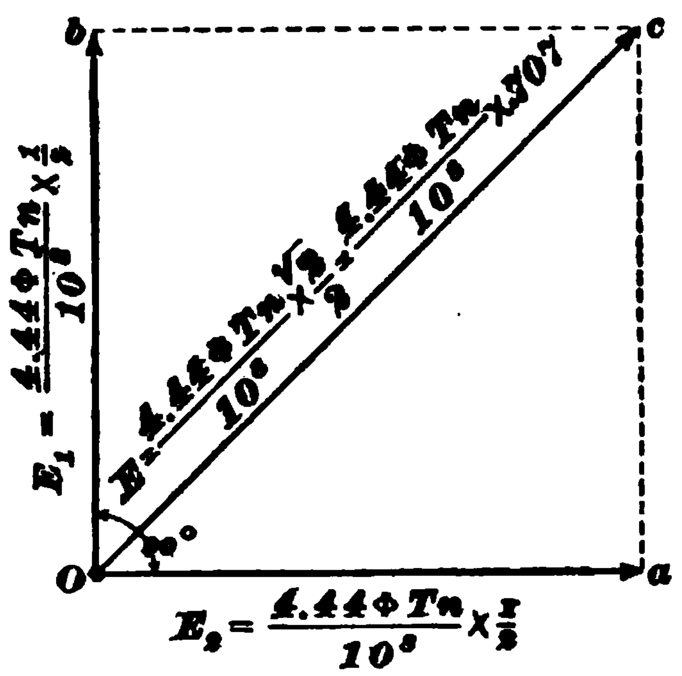


FIG. 9

$$E = \frac{4.44\ \Phi\ T n}{10^8} \times \tfrac{1}{2} \qquad (1)$$

since there are $\frac{1}{2}$ the total turns T active in each set. The resultant E. M. F. $O c$ will therefore be

$$E = \frac{4.44\ \Phi\ T n}{10^8} \times \tfrac{1}{2} \times \sqrt{2} = \frac{4.44\ \Phi\ T n}{10^8} \times .707 \qquad (2)$$

That is, *the E. M. F. that is obtained at no load from a two-coil single-phase winding is .707 times that which would have been obtained with the same total number of turns grouped into a uni-coil winding.* By spreading out the winding in this way, the no-load voltage has, for the same number of active conductors, been reduced about 30 per cent.; the inductance of the armature has, however, been reduced considerably; so that, although we may not get an armature that will give as high a voltage at no load, it may give as

high a terminal voltage when loaded, and a machine provided with such a winding would hold its voltage more nearly constant throughout its range of load.

33. The subdivision of the winding might be carried still further, and three slots for each pole piece used. The E. M. F.'s in the three sets of conductors would then be related as shown in Fig. 10. Each of the groups would

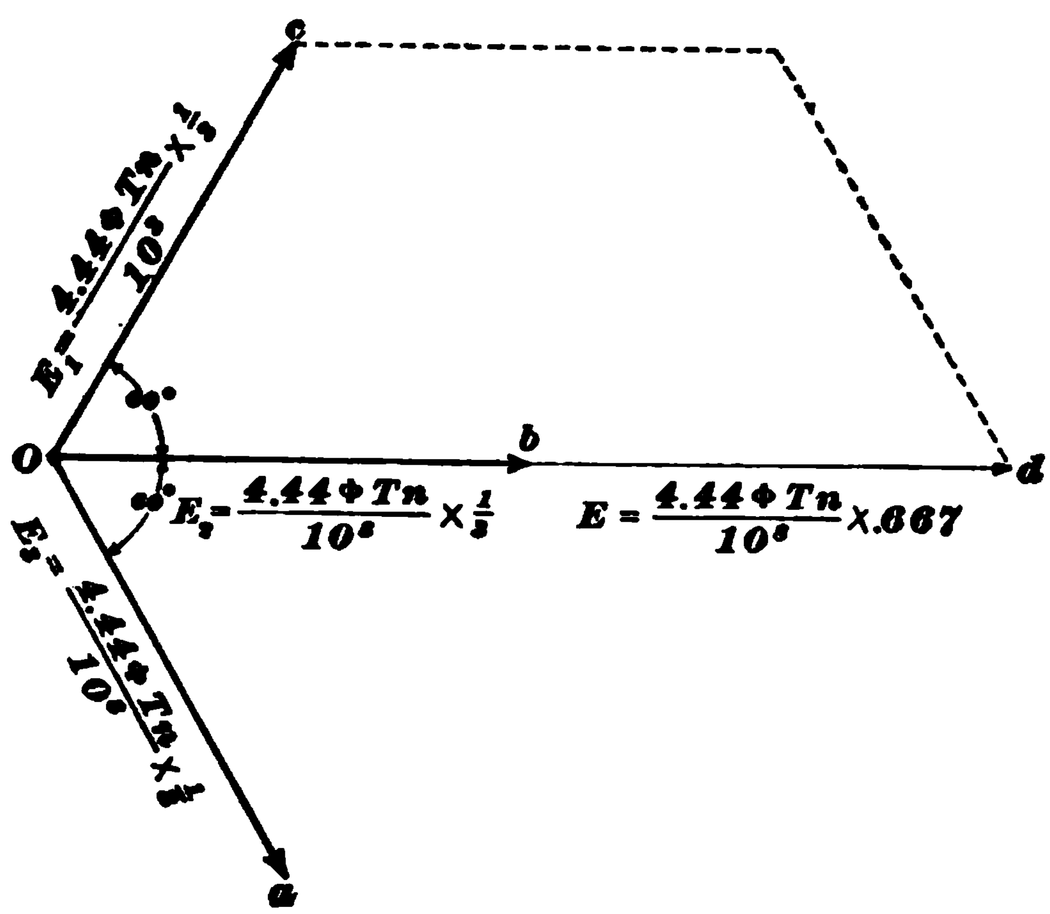


FIG. 10

consist of $\frac{T}{3}$ turns, and the three E. M. F.'s $O\,a$, $O\,b$, and $O\,c$ would be displaced 60° from each other, instead of 90°, as shown in Fig. 9, because there are three groups of conductors per pole, and the distance from center to center of the pole pieces corresponds to 180°. The E. M. F. generated in each set will be

$$E_1 = E_2 = E_3 = \frac{4.44\ \Phi\ T n}{10^8} \times \tfrac{1}{3} \qquad (3)$$

and the resultant E. M. F. $O\,d$, Fig. 10, will be

$$E = \frac{4.44\ \Phi\ T n}{10^8} \times \tfrac{2}{3} = \frac{4.44\ \Phi\ T n}{10^8} \times .667 \qquad (4)$$

The effect of spreading out the coils into a three-coil winding is, therefore, to reduce the no-load terminal E. M. F. still further, and at the same time to reduce the self-induction. It will be noticed that the difference in the voltages given by a two-coil and by a three-coil winding is not nearly so great as that between the voltages of the two-coil and single-coil windings. If the winding is spread out still more, the E. M. F. generated is reduced by very little, and if the subdivision is carried out so that the winding becomes uniformly distributed over the whole surface of the armature, the formula becomes

$$E = \frac{4.44\ \Phi\ T n}{10^8} \times .636 \qquad (5)$$

34. The more the winding is spread out, the greater the number of crossings of the coils at the ends of the armature, making such windings difficult to insulate for high voltages. Such windings, therefore, have the disadvantage of being more expensive to construct and insulate, in addition to giving a lower E. M. F. at no load for a given length of active conductor. They have the advantage of giving better regulation or small drop in voltage when loaded, and also give a smooth E. M. F. curve. Also, the heating is more uniformly distributed than when a concentrated winding is used. For single-phase armatures in general, we may then write the E. M. F. equation as follows:

$$E = \frac{4.44\ \Phi\ T n}{10^8} \times k \qquad (6)$$

where T = total number of turns *connected in series* on the armature;
Φ = total flux from one pole;
n = frequency;
k = constant depending on the style of winding used.

For a single-coil or concentrated winding, $k = 1$; for a two-coil winding, $k = .707$; for a three-coil winding, $k = .667$; for a uniformly distributed winding, $k = .636$.

POLYPHASE ARMATURE WINDINGS

35. Concentrated, or uni-coil, polyphase windings have already been described in the section on *Alternators.* The two- and three-phase windings there described consist of one group of conductors, or one slot for each pole and each phase. Polyphase windings can, however, be distributed in a manner similar to that just given for single-phase windings, and such distributed windings are in common use for induction motors, polyphase alternators, and polyphase synchronous motors. The distribution of such windings is accompanied by a lowering of the terminal E. M. F., as in the case of single-phase windings, though this decrease in the E. M. F. is not nearly so great. Suppose, for example, we have a three-phase winding with two groups of conductors per pole per phase. We will have then six groups of conductors for each pole, and as the distance from center to center of poles is equivalent to 180°, the E. M. F.'s in the two groups of each phase will differ in phase by $\frac{180°}{6}$, or 30°. Let the total number of turns per phase be T. Then, the number of turns in each of the two sets constituting each phase will be $\frac{T}{2}$, and the E. M. F. generated in each of the sets will be

$$E_1 = E_2 = \frac{4.44\, \Phi\, T n}{10^8} \times \frac{1}{2}$$

These two E M. F's will be related as shown in Fig. 11, and the resultant E. M. F. will be

$$E = \frac{4.44\, \Phi\, T n}{10^8} \times \frac{1}{2} \times 2 \cos 15°$$

$$= \frac{4.44\, \Phi\, T n}{10^8} \times .965 \qquad (7)$$

Hence, *the voltage generated per phase by a two-coil three-phase winding is .965 times that which would be generated by a single-coil winding.* In other words, the splitting up of the winding has resulted in a voltage reduction of but

$3\frac{1}{2}$ per cent. If a three-coil winding were used, the E. M. F. would be reduced still further, and if a uniformly distributed winding covering the whole surface of the armature were employed, the constant would become .95. If a uniformly distributed winding is used on a two-phase machine, the value of the constant becomes .90. For polyphase

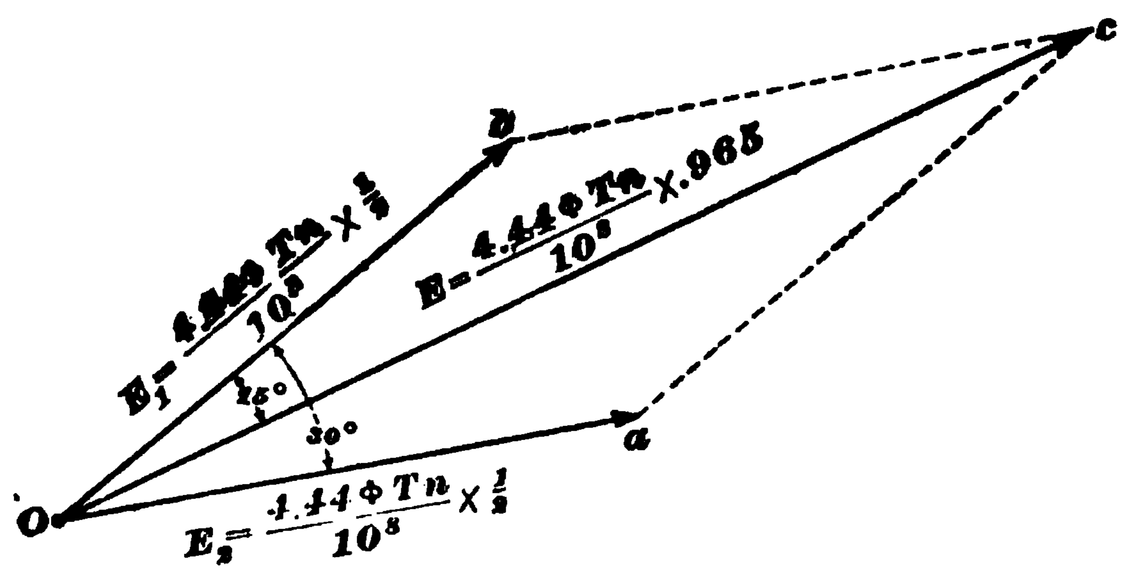


FIG. 11

windings we may then summarize the following: The E. M. F. *generated per phase* in a polyphase armature is given by the expression

$$E = \frac{4.44\,\Phi\,Tn}{10^8} \times k \qquad (8)$$

where T = number of turns connected in series *per phase*;
Φ = flux from one pole;
n = frequency;
k = constant depending on the arrangement of the winding.

For a winding with one group of conductors per pole per phase, $k = 1$; for a two-phase winding uniformly distributed, $k = .90$; for a three-phase winding uniformly distributed, $k = .95$; for a three-phase winding with two groups of conductors per pole per phase, $k = .965$.

The student will notice particularly that formula **8** gives the *voltage per phase*, not the voltage between the collector rings or terminals of the machine. This latter voltage will evidently depend on the method adopted for connecting the different phases together.

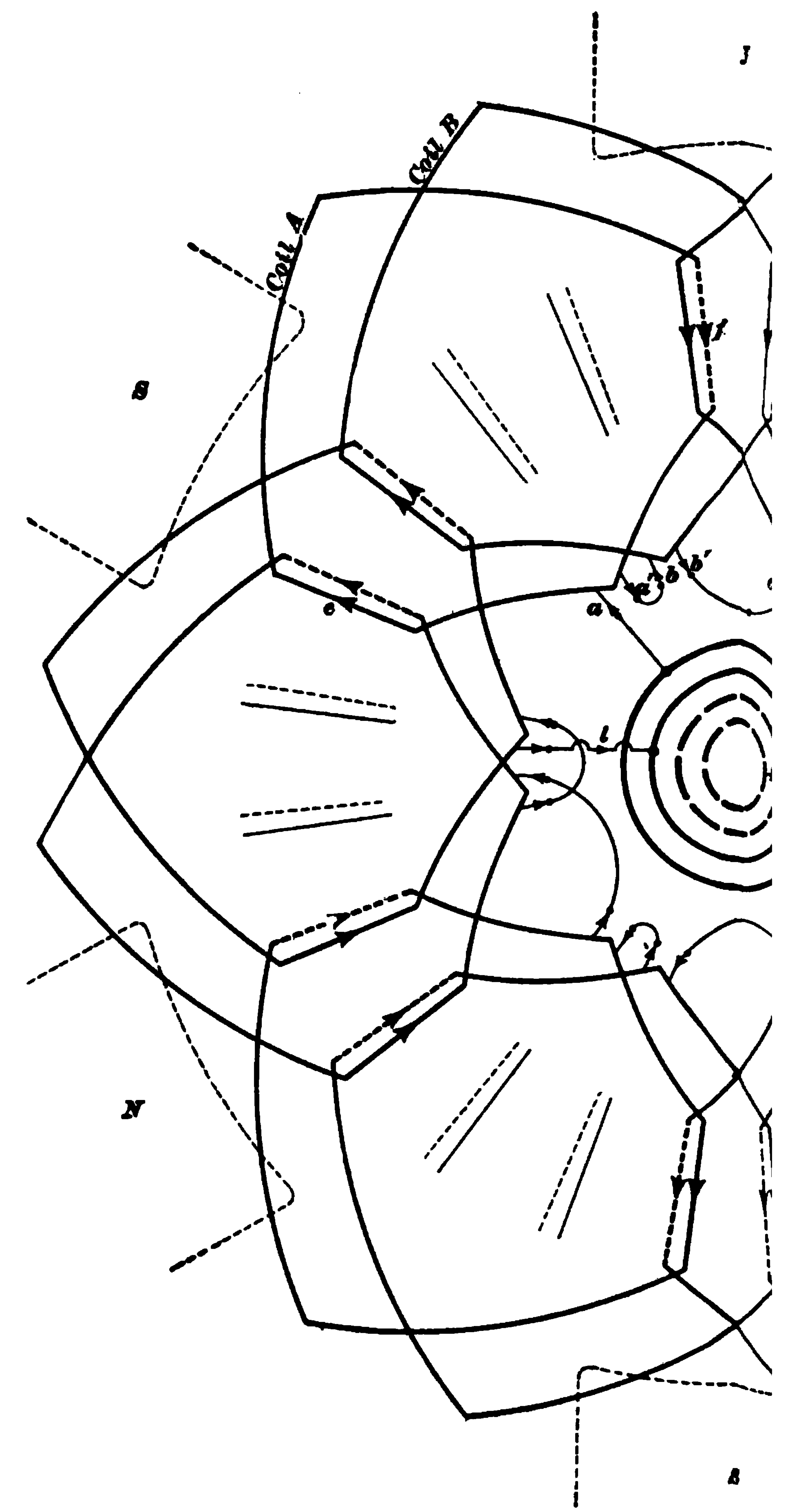
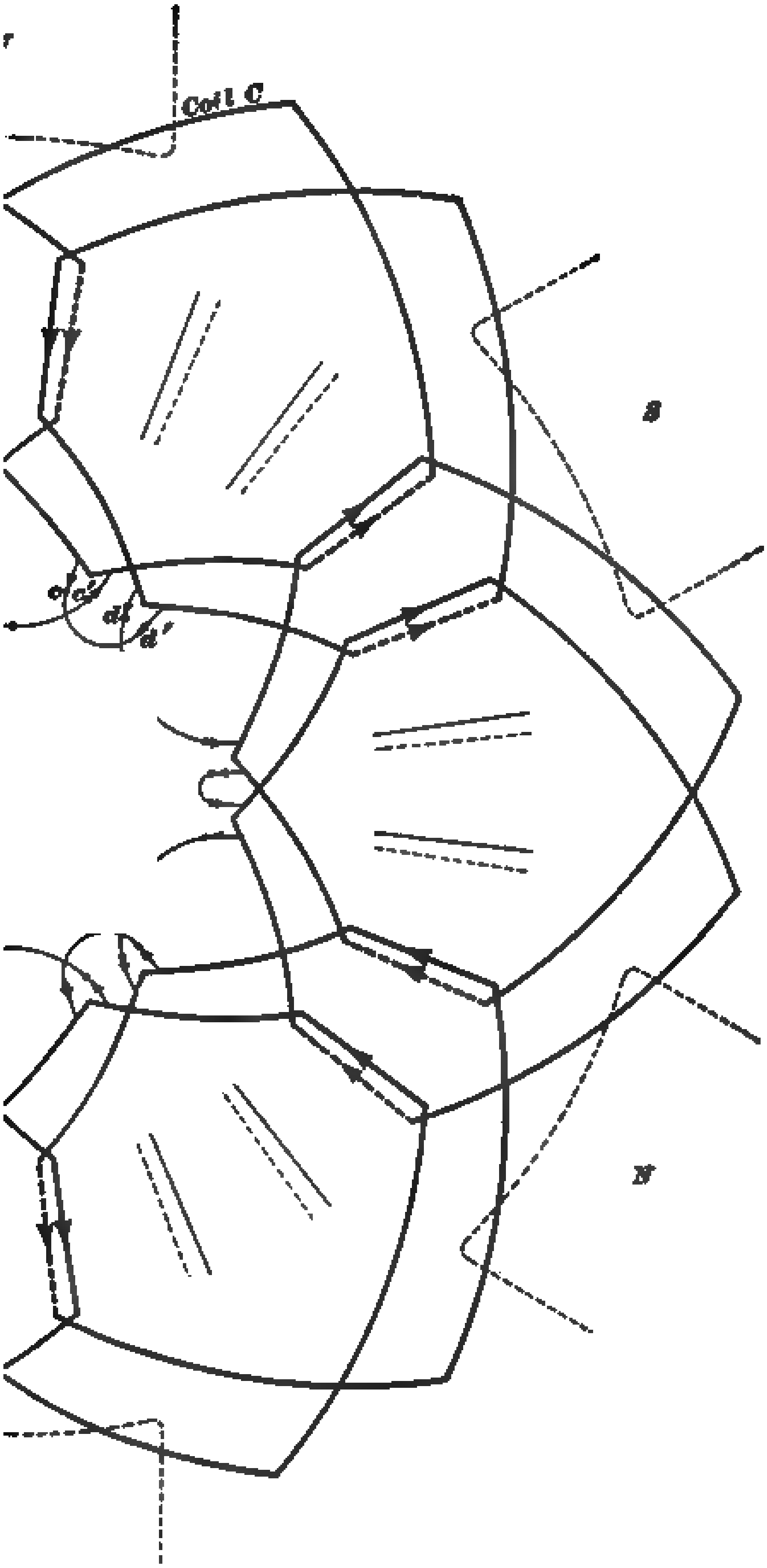
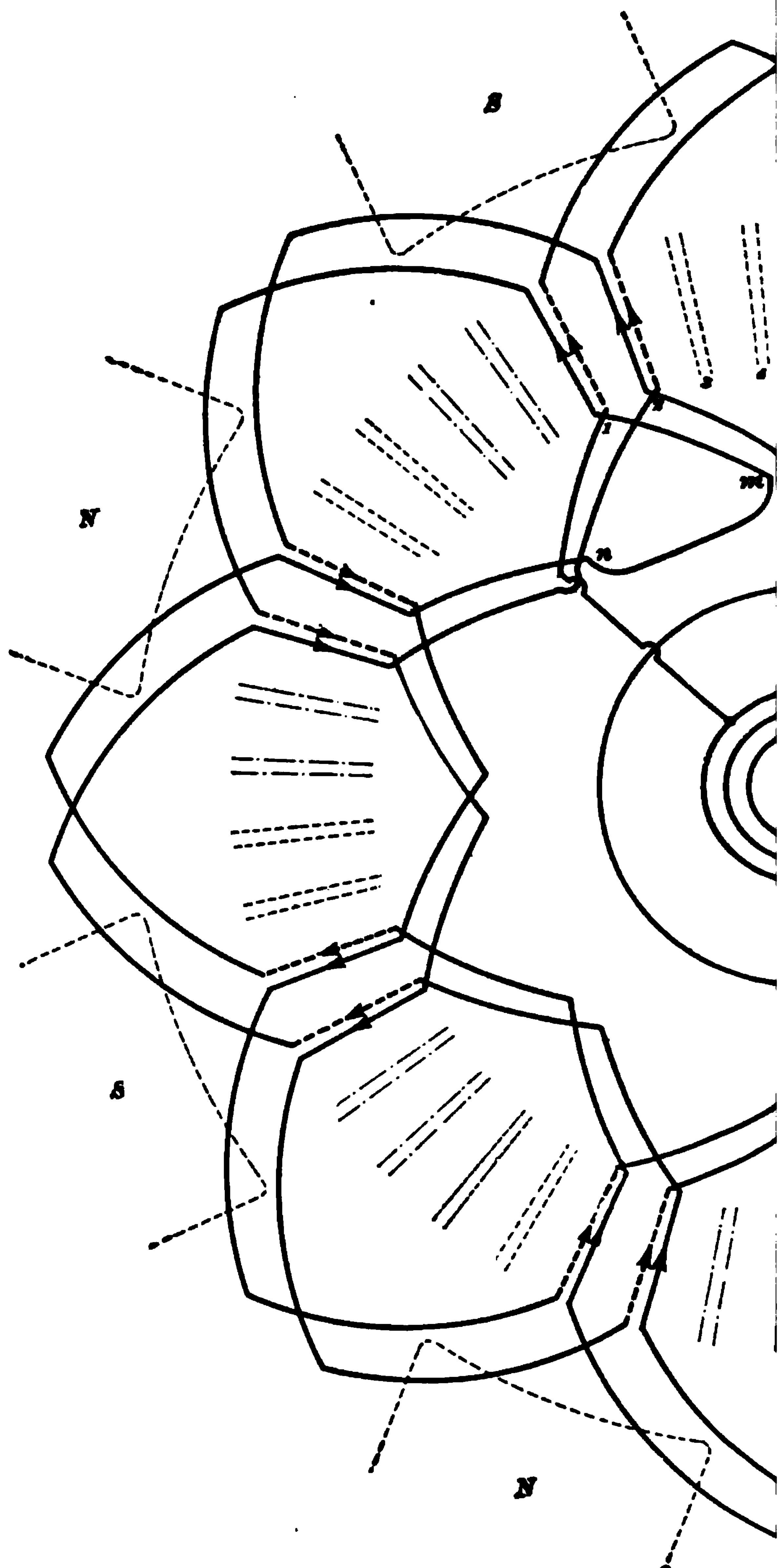


FIG. 12



. 12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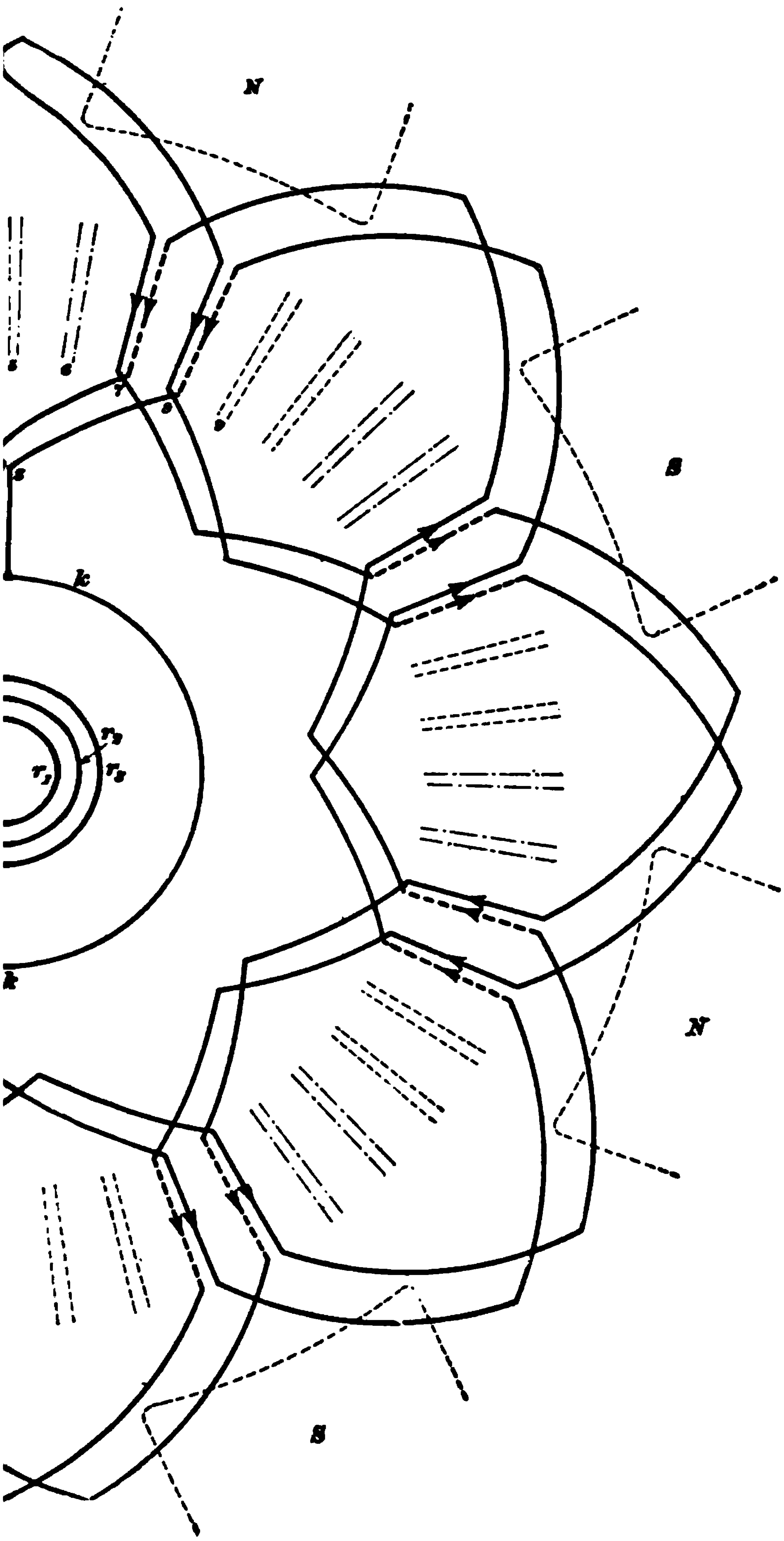


FIG. 13

ARRANGEMENT OF WINDINGS

36. The method of arranging these distributed windings will be understood by referring to Figs. 12 and 13. Fig. 12 shows a six-pole two-phase coil-wound armature with two slots per pole per phase. The coils are shown by the heavy outlines, the winding being in two layers, so that there are as many coils as slots. Only one phase is drawn in complete, so as not to confuse the drawing. Take the coil *A*. One side *e* of this coil lies in the top of a slot, and the other side *f* lies in the bottom of the corresponding slot under the next pole. The light lines *a*, *a'* represent the terminals of the coil *A*, and the light connections show the connections between the coils constituting one phase. Starting from collector ring *1*, we pass from *a* around coil *A* and come to *a'*; *a'* is joined to *b*, so that the current passes around coil *B* in agreement with the arrows; the terminal *b'* is then connected to *c'*, so as to pass through coil *C* in the direction of the arrows. This process is repeated until the twelve coils constituting the phase are all connected in series and the remaining terminal *l* is brought to collector ring *2*. The other phase, of which the active conductors are indicated by the light lines, is connected up in exactly the same way and its terminals brought to the collector rings *3* and *4*. This gives a completed two-phase winding that consists of two coils for each pole and each phase, all the coils in each phase being connected in series and each phase connected to its pair of collector rings.

37. Fig. 13 represents a three-phase bar-wound armature with two slots for each pole and each phase. The armature is wound for eight poles, so that there are 32 bars or conductors connected up in series in each phase. One phase is shown connected up, the conductors belonging to the other two phases being indicated by the dotted and dot-and-dash lines. Starting from the collector ring r_1, we connect to the bottom conductor in slot *1*; from there we pass to the corresponding slot under the next pole, that is, slot 7,

and connect to the top conductor in that slot. In this way we pass twice around the armature, connecting up the bars in accordance with the arrows, coming finally to the point *n*. From *n* a connection is made to *m*, and from *m* we pass twice around the armature again in the opposite direction, and come finally to the point *s*, which is connected to the common junction *k* if a **Y** winding is employed. This connects all the conductors belonging to this phase in series. The bars constituting the other two phases are connected in a similar way, and the three phases connected up in the **Y** or Δ combination, according to the rules that have been given in the section on *Alternators*. A three-phase alternator provided with a winding like that shown in Fig. 13 would be suitable for a machine designed to deliver a large current output at a low voltage. In such a case, the number of armature conductors required would be comparatively small, and bars could be used to advantage. A similar scheme of connection could be used for a coil-wound armature, except that each element of the winding would consist of a number of convolutions instead of the single turn, as shown in Fig. 13.

38. By referring to Figs. 12 and 13, it will be noticed that in such two-layer windings the top conductors are always connected across the front and back of the armature to bottom conductors; that is, a conductor in the top of one slot is not connected to the *top* conductor in the corresponding slot under the next pole. This is done to make the arrangement of the end connections such that they do not interfere with each other as already explained in connection with direct-current dynamos. The two-layer type of winding is on this account extensively used, and its application will be taken up further in connection with induction-motor design.

CONSTRUCTION OF ARMATURES

39. On the whole, the mechanical construction of alternator armatures is very similar to that employed for armatures for multipolar direct-current machines. There are differences in the electrical features, arising from the different type of winding usually employed and the absence of commutator connections. The construction of many of the armatures is simpler than that necessary for continuous-current machines, on account of the smaller number of coils used in making up the armature winding.

ARMATURE DISKS

40. Most of the armature disks used are adapted for armatures of the drum type. Such disks or disk segments are stamped from well-annealed mild steel. It is essential that whatever material is used, the hysteresis factor should be low, especially if the armature is to be run at a high frequency. It is almost the universal practice at present to use toothed cores, although smooth-core armatures were quite common in some of the older types of alternators. Core iron should be from .014 in. to .018 in., or from 14 mils to 18 mils, thick. Iron thicker than this is frequently used in direct-current machines, but it is not safe to use iron much thicker in alternator-armature cores on account of the danger of increasing the eddy-current loss. Some makers depend on the oxide on the disks for the insulation to prevent eddy currents, while other makers give the disks a coat of japan before they are assembled to form the core.

41. The variety of disks used for alternator armatures is large. Some are designed for stationary armatures of large diameter, while others are for rotating armatures of comparatively small diameter. The different styles of slots used are also numerous. Fig. 14 represents a common style

of disk used for lighting alternators. This disk is provided with as many teeth and slots as there are poles on the alternator. Each tooth is provided with the projections *a*, *a*, which hold the coils in place and obviate the necessity of band wires. A keyway *k* is provided by which the disks are keyed to the spider supporting them. It is well to notice, in passing, that core disks for alternators are usually quite shallow, the depth of iron *d* under the slots being small compared with that usually found in direct-current armatures, making the disks appear more like rings. This is accounted for by the fact that in an alternator the total flux that the armature conductors cut in one revolution is divided up among a large number of poles; consequently, the flux from any one pole is comparatively small. The flux through the core under the teeth is one-half the flux from the pole piece; the cross-section of iron necessary to carry it is therefore small, and a large depth of core is unnecessary to obtain the required cross-section.

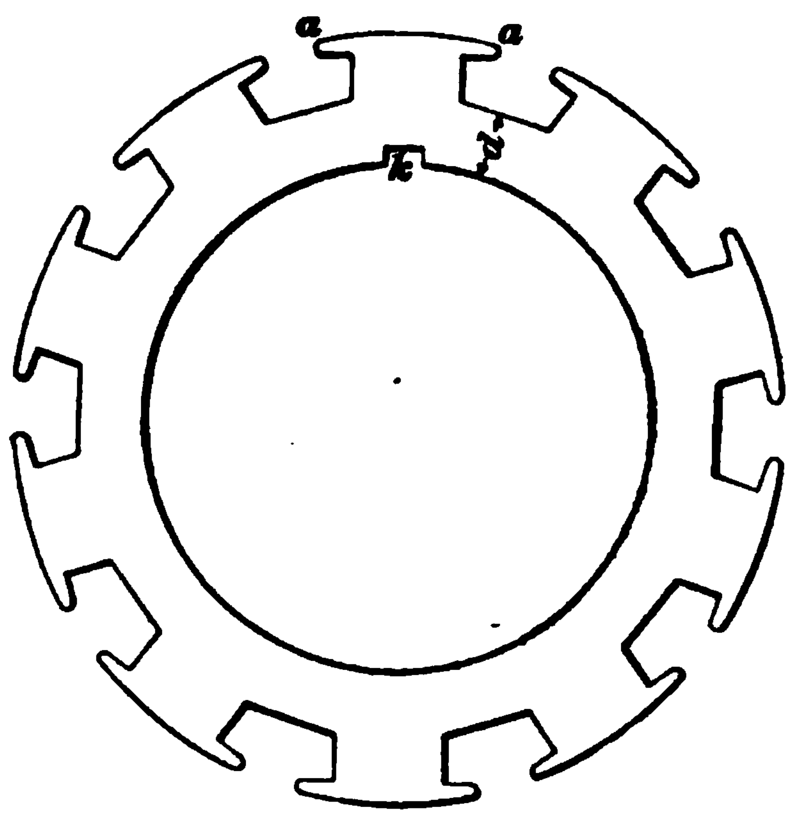


FIG. 14

42. Fig. 15 shows another style of disk and slot in common use. This disk is provided with 16 slots, and would be suitable for an eight-pole two-phase winding. The same style of disk with 24 slots would answer for the three-phase winding.

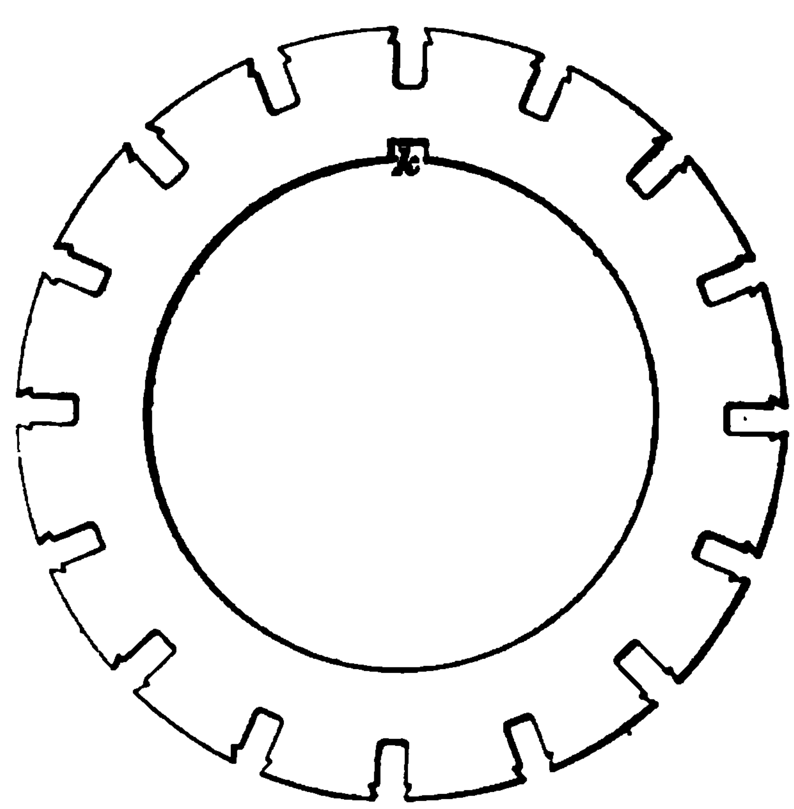


FIG. 15

The disk shown in Fig. 15 is provided with slots that have dovetailed grooves near the circumference. After the coil is placed in position, a wooden wedge is fitted into these grooves, thus holding the coil firmly in place and doing away with the necessity of band wires.

43. When the armature is wound with bars, straight slots are frequently used. Fig. 16 shows such a disk provided with 48 equally spaced slots. A disk of this kind would be suitable for an armature core for the winding shown in Fig. 13. It would be necessary in this case to use band wires to hold the conductors down in place, giving a construction very similar to that commonly employed for direct-current armatures.

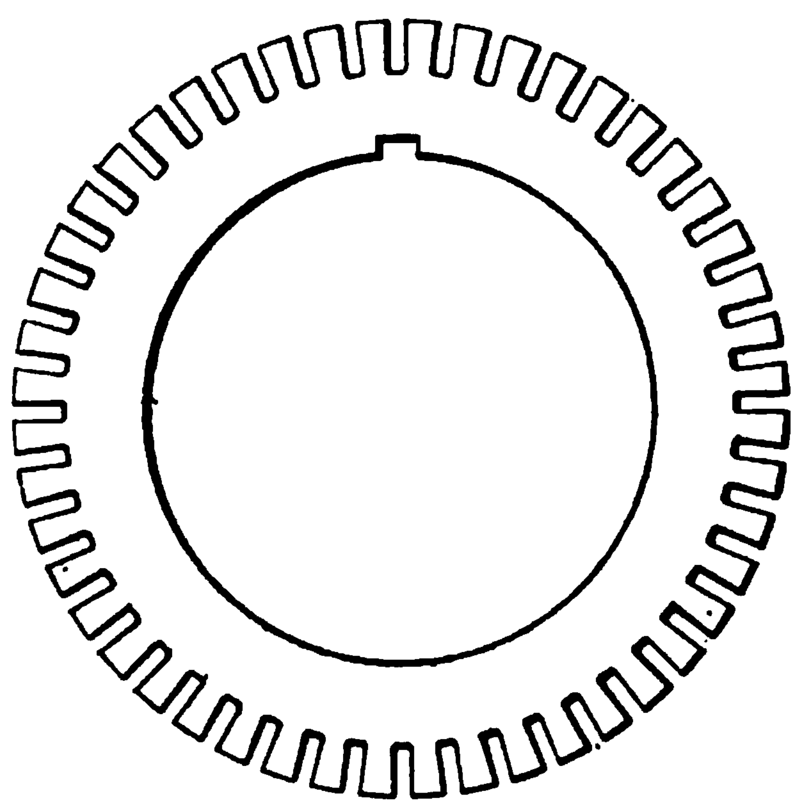


FIG. 16

44. Stationary armatures for large machines are placed externally to the revolving field, and the coils are placed in slots around the inner periphery. Since such armature cores are generally of large diameter, the armature disks have to be punched out in sections, as shown at *c* in Fig. 17. These sections are provided with dovetail projections *b* that fit into slots in the

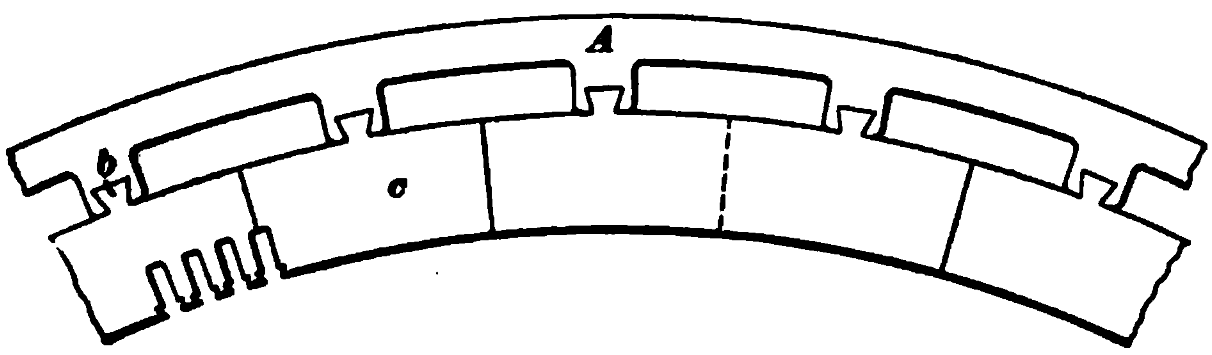


FIG. 17

supporting iron framework *A*. As the core is built up, the joints between the different segments are staggered, or the

segments are overlapped, so as to form a core that provides a magnetic circuit practically as good as if the disks were punched in one piece. The use of the dovetail projecting lugs avoids the use of bolts passing through the disks to hold the latter in place. Unless bolts are insulated, they are liable to give rise to eddy currents by short-circuiting the disks. Some makers, however, use disks as shown in Fig. 18, provided with holes *h* for the clamping bolts. The slots used for such stationary armatures must of course be provided with grooves of some kind to receive holding-in strips or wedges, as it is not possible to use band wires in such a case.

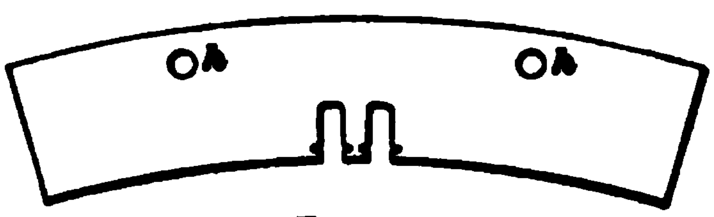


FIG. 18

45. Revolving armatures are also frequently made of such large diameter that it is not practicable to punch the disks in one piece. In such cases, again, the disks are made in segments, and are held in place either by bolts passing through them or by dovetail projections fitting into grooves in an extension of the armature spider arm. This construction will be understood by referring to Fig. 19. In assembling disks to make up a core, it is usual to place a heavy sheet of paper about every ½ inch or ¾ inch of core, in order to make sure that the path for eddy currents will be effectually broken up.

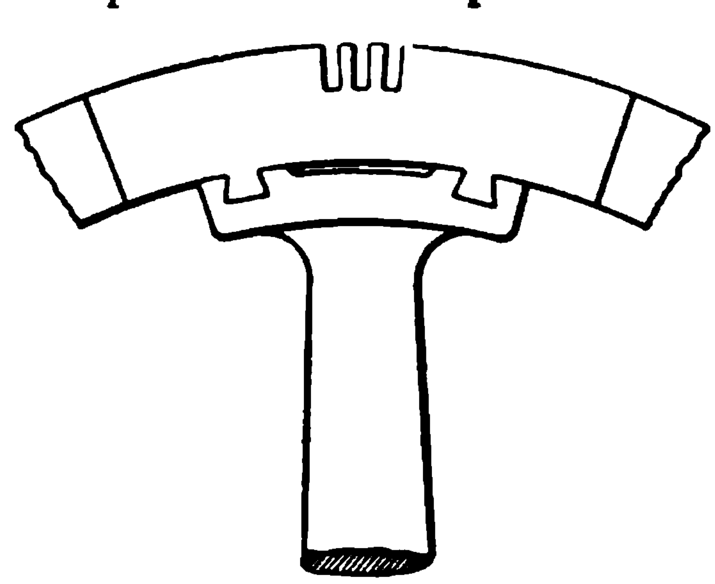
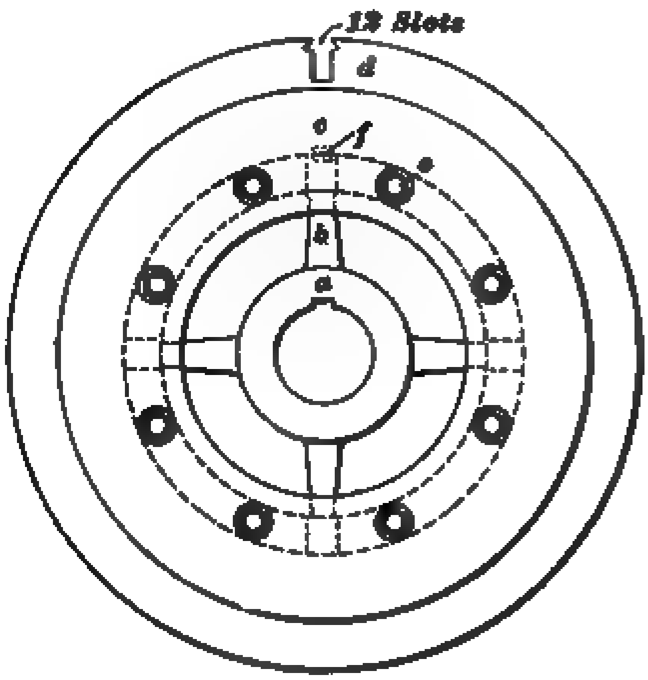


FIG. 19

ARMATURE SPIDERS

46. Disks for revolving armatures are usually supported on spiders similar to those used for direct-current multipolar armatures. These spiders are made of cast iron or steel,

and are necessarily strongly constructed. They should be so made as to clamp the disks firmly in place, and be amply strong to bear any unusual twisting action they may have to withstand due to an accidental short circuit. Fig. 20 shows two views of a spider and core suitable for disks of moderate size punched in one piece. The spider proper consists of a



(a) (b)

FIG. 20

hub *a* provided with four radial arms *b* that fit the inner diameter of the disk. The hub is bored out so that it fits very tightly on the shaft, and a key is provided to avoid any chance of turning. The core disks *d* are clamped firmly in place by two heavy cast-iron end plates *c*, *c* that are pressed up and held by the bolts *e*. These bolts pass under the disks, so that there is no danger of their giving rise to eddy currents. The key *f* prevents the disks from turning on the spider and insures the alinement of disks, which is necessary to make the teeth form smooth slots when the core is assembled.

Fig 20 shows the construction used with armatures having a small number of heavy armature coils. In such cases

the coils are stiff and the ends project out past the end of the core without being supported. In case a distributed winding is used, the coils are numerous, and being small, they are frequently not stiff enough to support themselves; hence, the clamping rings of the spider are in such cases provided with flanges, as shown in Fig. 21. The end connections of the coils lie on the flat cylindrical surfaces *a*, *a*, and are tightly bound down in place by means of band wires. Fig. 22 shows a spider suitable for a large armature built up with segments like those shown in Fig. 19. This style of spider

FIG. 21

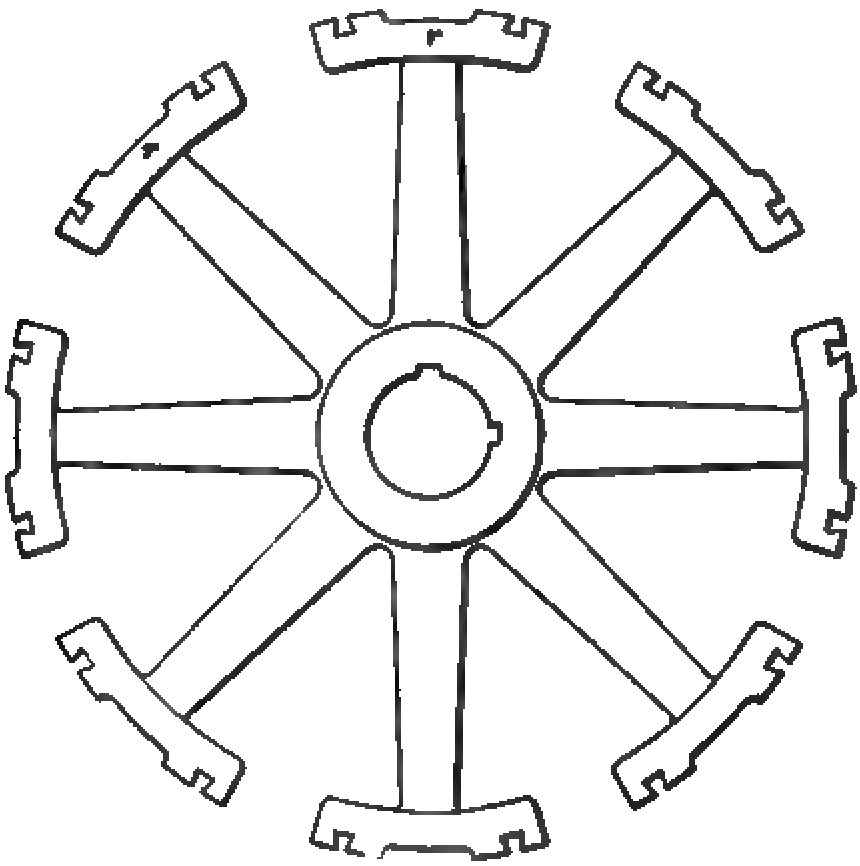


FIG. 22

is common for machines with large diameter of armature

running at low speeds. The rim *r* of the spider is made non-continuous, in order to avoid strains in casting as much as possible.

47. When the armature is the stationary part of the machine, a stationary frame of some kind must be used to support the stampings. This consists usually of a rigid cast-iron framework provided with end plates, between which the armature disks are clamped. The construction will be understood by referring to Fig. 23, which shows a

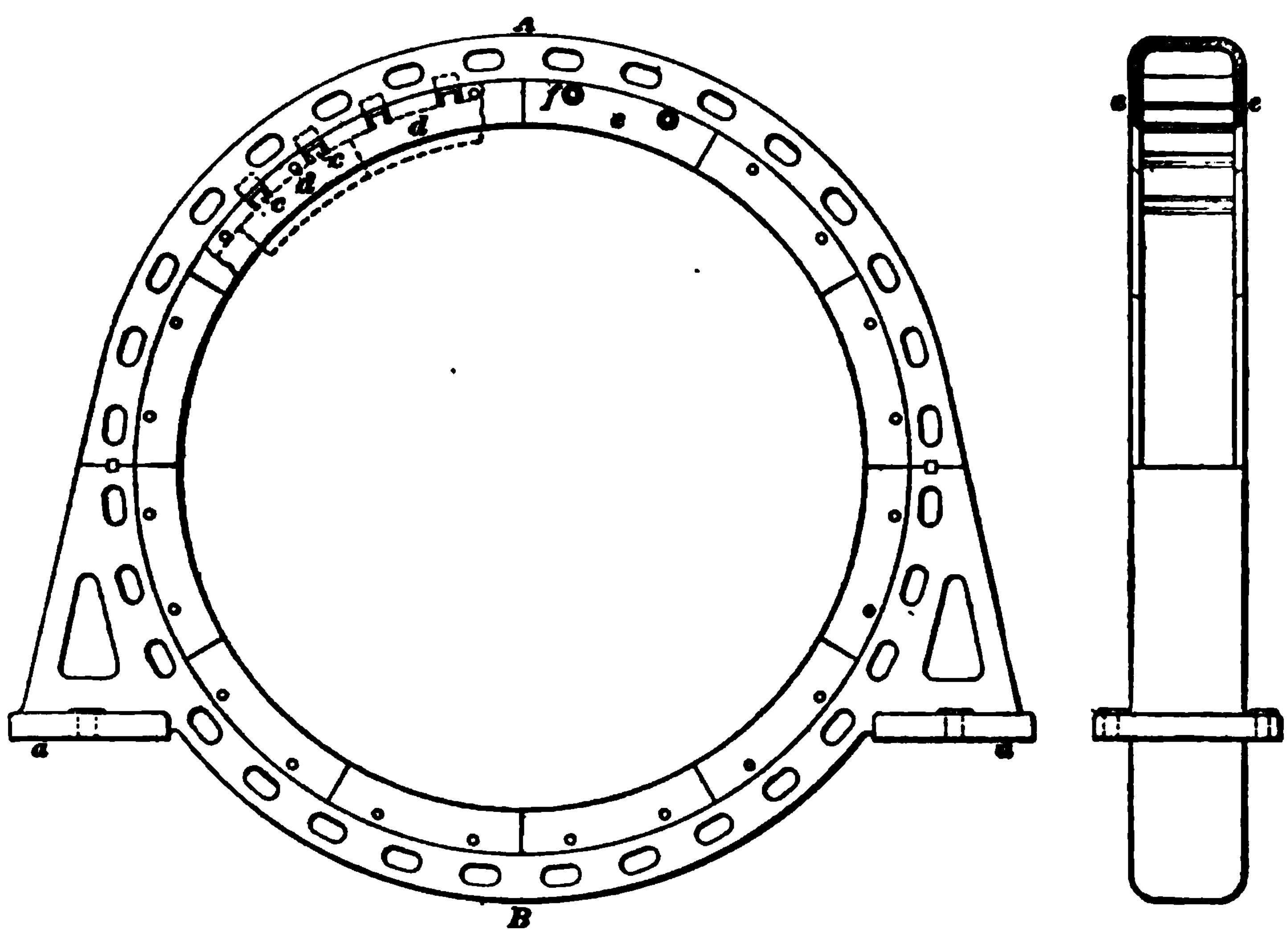


FIG. 23

stationary armature frame for a machine of large diameter. The frame casting is usually made in two pieces *A* and *B*, the lower half being provided with projections *a*, *a*, by which the spider is bolted to the bed or foundation. The segmental core stampings *d*, *d* are held in place by the dovetail grooves *c*, *c*. These segments are clamped between the end rings *e*, *e* by means of the bolts *f*. The end rings *e* are shown made up in segments on account of their large diameter.

ARMATURE CONDUCTORS

48. The style of conductor used on the armature will depend to a great extent on the current that it is to carry and the space in which it is to be placed. High-voltage machines of moderate output are usually wound with double or triple cotton-covered magnet wire. Frequently two or more wires are used in multiple in order to secure the requisite cross-section. This gives a more flexible conductor than a single large wire, which would be difficult to wind.

49. It is often advantageous to use bare wire in making up such conductors and cover the combination of wires with insulation, as shown in Fig. 24.

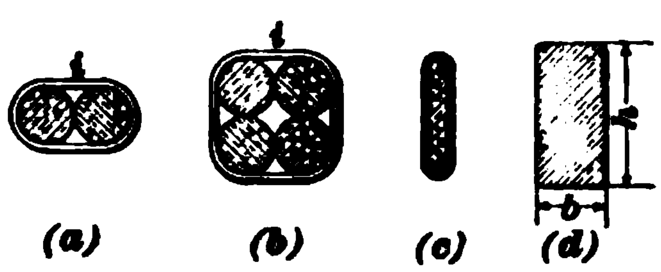


FIG. 24

A section of a conductor made up of two bare wires in multiple is shown at (*a*), and four bare wires at (*b*), the conductors being in each case covered by the cotton wrapping *i*. This construction not only saves space, but the insulation also serves to hold the wires in place. Conductors of special shape are used on some machines. For example, square wire and copper ribbon are often employed. Fig. 24 (*c*) shows a section of a copper ribbon conductor with its cotton insulation. Such ribbons are usually from $\frac{1}{32}$ inch to $\frac{1}{16}$ inch thick, and should be made with rounded edges, to prevent danger of cutting through the insulation.

50. Copper bars are largely used for armatures designed to deliver large currents. Fig. 24 (*d*) shows a cross-section of an armature-winding bar. The dimension *h* is usually considerably greater than *b*, in order to adapt the bar to an armature slot that is deep and narrow. These bars are rolled to any required dimensions, the corners being slightly rounded, as shown, to prevent cutting of the insulation.

FORMS OF ARMATURE COILS AND BARS

51. The simplest form of coil for alternator armatures is that used on ordinary single-phase machines with uni-coil windings. The coils usually consist of a fairly large number of turns, and are wound on forms, so that the finished coil is of such shape that it fits snugly into place in the slots. Such coils are heavily taped to insulate them thoroughly and make them hold their shape. Coils of this type are shown in Fig. 25 (*a*) and (*b*). The straight portion *c c* and *d d* lies in the slots, the end parts projecting out over the ends of the armature core. In some cases the ends are curved as at (*a*), while in others the ends shown at (*b*) are used.

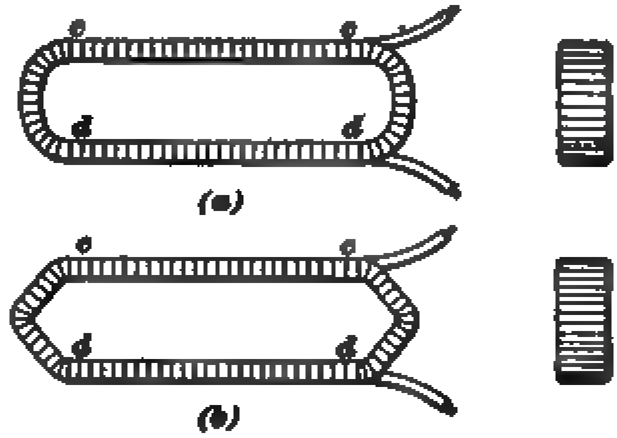


FIG. 25

52. In many polyphase windings it is necessary to shape these heavy coils so that they may cross each other at the ends of the armature. This is accomplished by shaping one of the coils as shown in Fig. 26. The end of the coil *b* is bent down into a different plane from that of *a*, so that the coils cross each other without touching, and insure good insulation.

FIG. 26

53. When coils are used for a distributed winding like that shown in Fig. 12, they are generally shaped like the coil shown in Fig. 27, which is the same as those used on barrel-wound direct-current armatures. This is a form-wound taped coil, consisting usually of a comparatively

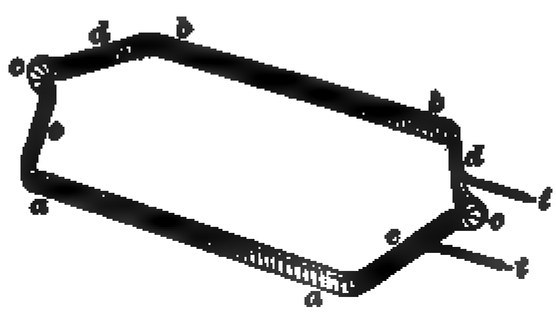


FIG. 27

small number of turns. The straight portions *a a* and *b b* lie in the slots, while the end portions project beyond the core and are usually supported by flanges, especially if the armature revolves. The side *a a* lies in a lower plane than *b b*, so that the upper and lower end connections do not interfere with each other. The terminals *t*, *t* of the coil are usually brought out at the points shown. At the points *c*, *c* the coil is so formed as to bring the end connections *d*,*d* into a plane above *a*, *a*, and thus bring the side *b b* in the top of the slot. Sometimes the terminals are brought out at the corners *a*, *b*, if this brings them in a position more convenient for connection to the other coils.

54. Bar windings are frequently made in two layers. Fig. 28 shows a form of bar suitable for a winding such as that shown in Fig. 13. The straight part *a a* lies in the slot, and the end portions *b*, *b* form the connections to the other bar.

FIG. 28

Fig. 29 shows one element or turn of such a winding. The part *c c* lies in the top of the slot, and the two bars making up the element are soldered together at the point *d*. Fig. 30 shows a similar element for a wave bar winding, except that there is no soldered joint at the point *a*, the element being composed of one continuous copper bar first bent into the long **U** form shown in Fig. 31, and then spread out to form the winding element shown in Fig. 30. Bars of the style just described are used also for some styles of induction-motor armatures. The portion of the bar forming the end connection has to be taped in order to insulate it from its neighbors. The part in the slot is frequently taped also, though in some cases the insulation from the core is provided wholly by the insulating trough.

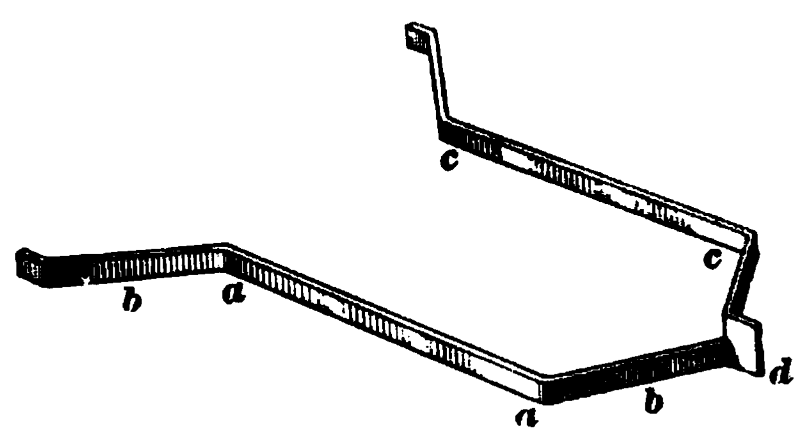


FIG. 29

Fig. 32 shows a portion of the bar winding on the stationary armature of one of the large 5,000-kilowatt alternators of the Manhattan Elevated Railway, New York. In this case there are three bars in each slot, the bars being first insulated separately and then bound together. The figure shows the arrangement of the end connections in two

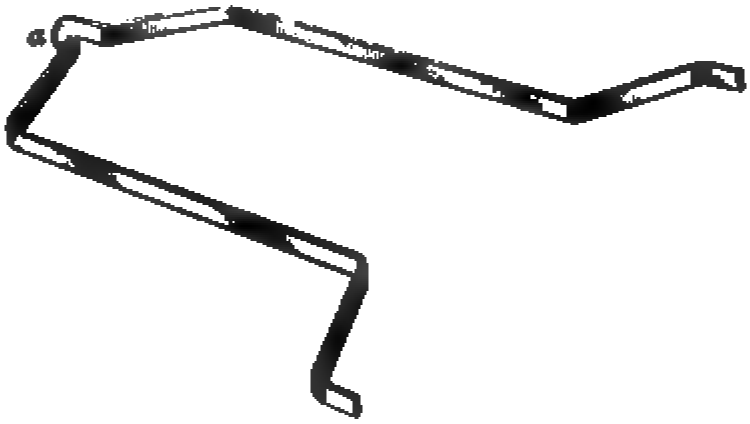


Fig. 30

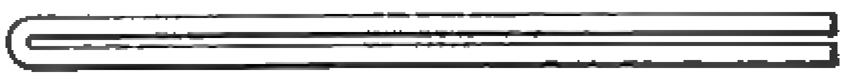


Fig. 31

different planes, so that they can pass each other with a good clearance. This armature has a distributed winding

Fig. 32

with 4 slots or 12 conductors per pole per phase. The armature is wound for three phases and delivers current at 11,000 volts.

ARMATURE INSULATION (COILS)

55. Alternator armatures are generally called on to generate much higher voltages than are common with continuous-current machines. The pressures generated by ordinary lighting alternators are usually in the neighborhood of 1,000 or 2,000 volts. Power-transmission alternators with stationary armatures have been built to generate as high as 10,000 or 12,000 volts. These are the values of the pressures generated in effective volts, and when it is remembered that the *maximum* value of the pressure to which the insulation is subjected is considerably greater than the effective value, it will be seen that the insulation of these armatures must be carefully carried out to insure against breakdowns. The insulation should be capable of standing a pressure at least three or four times as great as that at which it is ordinarily worked.

56. For very high-voltage machines it is best to use the type with stationary armature, as it is easier to insulate a stationary armature thoroughly. The allowable space for insulation on a stationary armature is usually greater than on a revolving one, and, moreover, the insulation is more likely to remain intact. A revolving armature also necessitates collector rings, brush-holder studs, etc., which have to be insulated for high pressures; whereas with the stationary armature only three terminals are required, which are comparatively easy to insulate.

57. When the coils each contain a large number of turns, the voltage generated per coil will be large; consequently, it is not only necessary to insulate the outside of the coil thoroughly, but each layer must also be insulated from its neighbor. Fig. 33 shows a section of a coil consisting of 32 turns. Between each layer of wire is a layer of

FIG. 33

insulation *i* turned up at the ends, so as to thoroughly insulate the individual layers. The whole coil is covered with a heavy wrapping of insulating tape *t*, and in addition is baked to drive out all moisture and treated with insulating varnish. The thickness of tape will depend on the voltage of the machine. Linen tape of good quality, treated with linseed oil, forms about the best material for this purpose, as it has high insulating properties and does not deteriorate with a moderate amount of heating Such tape is usually about .007 to .010 inch (7 to 10 mils) thick, and is wound on half lapped. Where extra high insulation is required, the tape may be interleaved with sheet mica. Coils for distributed windings do not usually contain a large enough number of turns to require insulation between the separate layers. They may be taped and treated with the same materials as the heavier coils, but the outside taping is usually not so heavy. With such windings, the material lining the slot is depended on largely for the requisite insulation.

ARMATURE INSULATION (SLOTS)

58. The taping on the coils is not always depended on alone for the insulation. The slots are often lined with insulating material that is not likely to be damaged by putting the coils in place. Slot insulation is usually made up in the form of troughs or tubes composed of alternate layers of pressboard and mica. The mica is depended on mainly for the insulation, the pressboard being used as a bonding material to hold the mica in place. These tubes may be either made up separately or formed in place in the slots. The mica is usually stuck on the pressboard with shellac or other insulating varnish, which becomes dry when hard and makes the trough hold its shape. Fig. 34 shows the slot insulation for an armature made up of disks similar to those shown in Fig. 13. The hardwood strip *a* is first

laid in the bottom of the slot, and the paper and mica trough *b* formed in place before the bonding varnish becomes dry. The coil *c*, consisting of several turns of copper wire or ribbon, is wound in place after the slot insulation has

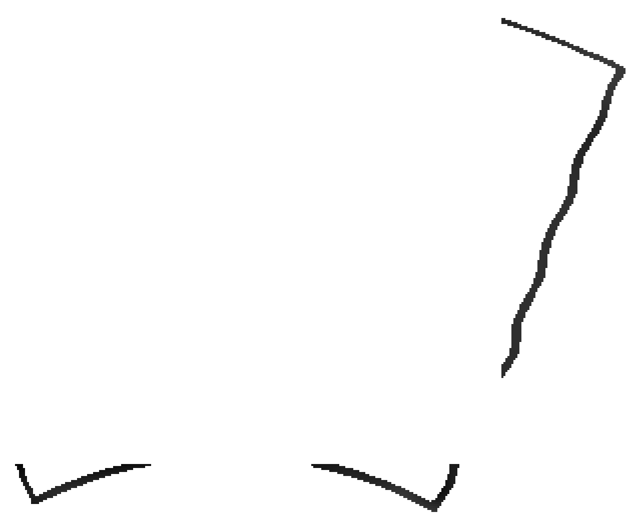


FIG. 34

become dry, and a wooden wedge *d*, pushed in from the end of the armature, holds the winding firmly in place. An insulating piece *e* is also placed between the wedge and the winding.

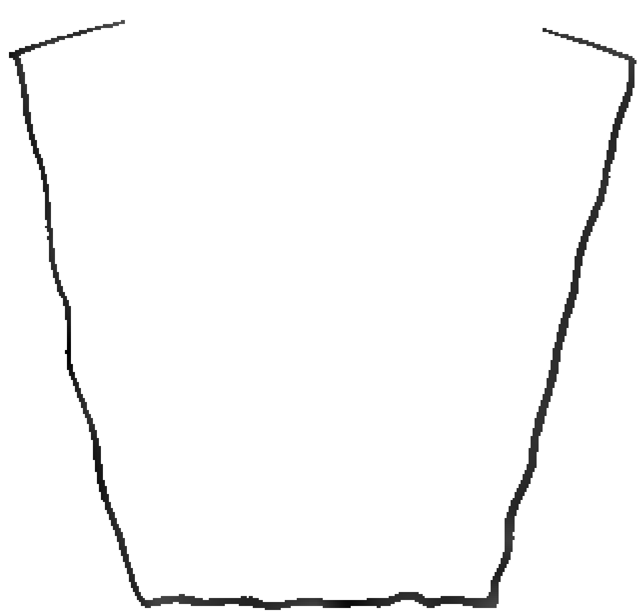


FIG. 35

59. Fig. 35 shows another form of slot insulation; *t* is the taping on the coil and *i* the paper and mica insulating trough. The top of the trough is left projecting up straight until the coil is placed in the slot, after which it is bent over as shown, protecting the coil from any injury while the wedge *a* is being forced into place. These wedges should be cut so that the grain of the wood lies across

the slot, otherwise there is danger of their becoming loose due to shrinkage.

60. Fig. 36 shows the arrangement of slot insulation for a coil-wound two-layer armature. The insultating trough *i* runs around the slot and laps over the top of the coil as before. In addition to this, the upper and lower groups of conductors are separated by the insulating strip *a*, which must be sufficiently thick to stand the total voltage generated. This arrangement also makes use of the wedge construction for holding the coils in place.

FIG. 36

61. Fig. 37 shows the insulation for a two-layer bar-wound armature with straight slots. This style of slot would be suitable for the bar winding shown in Fig. 13. In such cases the bars have to be placed in the slots from the top, the bent ends preventing their being pushed in from the end. This necessitates the use of straight slots and band wires for holding the bars in place. A wooden strip is usually inserted between the band wires and bars in order to protect the winding.

FIG. 37

62. The present practice in armature construction, especially for high pressures, is to place the insulation on the coil rather than in the slot. The coils after being wound are first thoroughly baked and then placed in hot insulating compound under pressure, so that the insulating varnish is forced into the coil. The coil is then taped with several layers of oiled linen, each layer being treated with varnish and baked before the next is applied. This gives a dense hard insulation that offers a high resistance to puncture and is more homogeneous than the ordinary slot insulation. The only insulation used in the slot itself is a thin layer of leatheroid or fiber to prevent abrasion of the coil while it is being forced into position.

63. In using two-layer windings, care should be taken to have the top and bottom layers very thoroughly insulated from each other. The insulating troughs *a*, Fig. 38, should project a short distance beyond the core *d*, in order to make sure of good insulation between the coils and core. The spider flanges should also be thoroughly insulated with paper and mica *c* wherever there is any possibility of the current jumping from the coils to the spider.

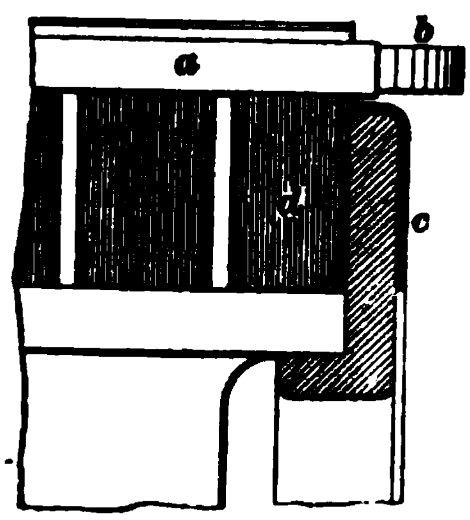


FIG. 38

MAGNETIC DENSITIES

DENSITY IN ARMATURE TEETH

64. Where armatures are wound with a few heavy coils, the teeth between the coils are large, in some cases nearly as wide as the pole faces. In such armatures the magnetic density in the teeth will not be much higher than that in the air gap. When a distributed winding is used, the surface of the armature is split up more by the slots, and the area of cross-section of iron in the teeth is reduced. This gives rise to a higher magnetic density in the teeth than in the air gap.

65. It was pointed out, in connection with the design of continuous-current machines, that in such machines it was desirable to have the magnetic density in the teeth high, because highly saturated teeth prevent the armature from reacting strongly on the field and thus aid in suppressing sparking. In the case of alternators, however, high densities in the teeth are avoided, because the effects of armature reaction are not nearly so serious in these machines, and the high density might prove detrimental by causing excessive hysteresis and eddy-current losses. In general, therefore, in alternator design, the magnetic density in the

core teeth is kept as low as possible. The density, however, cannot be made very low, as this would mean large teeth and a correspondingly large armature. Where distributed windings are used, it will generally be found that the width of the slot and width of tooth are made about equal, thus reducing the effective iron surface of the armature to about one-half and making the magnetic density in the teeth about twice that in the air gap. It will be remembered that both the hysteresis loss and eddy-current loss increase very rapidly with the density; consequently, it is easily seen that if the density in the teeth is very high, the amount of loss in them may be considerable, on account of the high frequency at which alternators usually run. It also follows that, for the same amount of loss, it would be allowable to use a higher magnetic density with a low-frequency alternator than with one running at a high frequency.

DENSITY IN ARMATURE CORE

66. The density in the armature core proper, that is, the portion of the core below the armature slots, should also be low, in order to keep down the core losses. This density can be made almost as low as we please by decreasing the inside diameter of the core, thus making the depth *d*, Fig. 14, large, and increasing the cross-section of iron through which the lines have to flow. If, however, the inside diameter were made very small, the core would be heavy, and since the hysteresis loss is proportional to the volume of iron, very little would be gained by decreasing the density beyond a certain amount. Armature cores for alternators are usually worked at densities varying from 25,000 to 35,000 lines per square inch, the allowable density being higher in low-frequency machines than in those running at high frequencies. Where armatures are run at very high speeds of rotation, the density may be allowed to run a little higher than the above values, in order to make the core as light as possible, provided the frequency is not too high.

DENSITY IN AIR GAP

67. The allowable density in the air gap will depend, to a certain extent, on the material of which the pole pieces are made. If cast-iron pole pieces are used, the density must be kept fairly low, otherwise there will be danger of the cast iron becoming saturated. It is best, therefore, to make the air-gap density in such machines in the neighborhood of 30,000 lines per square inch. If the pole pieces are made of wrought iron, as they nearly always are in modern machines, the density may be as high as 40,000 or 60,000 lines per square inch. The density could be even higher than this without danger of saturating the wrought iron, but if the air-gap density is carried too high, a very large magnetomotive force must be supplied by the field coils in order to set up the flux. For these reasons the average air-gap density should usually be somewhere near the values given above.

DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 2)

DESIGN OF 100-KILOWATT SINGLE-PHASE ALTERNATOR

1. The general considerations governing the design and construction of alternator armatures having been given, we will now apply these to the special case of the design of an armature for a single-phase alternator, in order to illustrate the calculation of the different dimensions. As a starting-point, we will assume that the following quantities are known, and in this particular case are as given below, the design being worked out from these quantities. The student will understand, however, that most of the formulas are perfectly general, and that these special values are only taken to illustrate a typical case in order to make the design clearer. The following quantities are in general known or assumed: (1) Output at full load; (2) frequency; (3) speed; (4) voltage at no load, voltage at full load; (5) allowable safe rise in temperature; (6) general type of machine.

For the case under consideration we will take the following: (1) Output at full load, 100 kilowatts; (2) frequency, 60 cycles per second; (3) speed, 600 revolutions per minute; (4) voltage at no load = 2,000 = E, voltage at full load = 2,200 = E'; (5) allowable rise in temperature, 40° C.; (6) general type of machine, belt-driven, revolving armature, stationary field.

2. It will be noted that the armature is to deliver 2,000 volts on open circuit and 2,200 volts when the machine is fully loaded. This is done so that the voltage at the distant end of the line may remain practically the same from no load to full load. This increase in voltage is accomplished by strengthening the field by means of the series-coils, so that, so far as the voltage generated by the armature is concerned, we design it to generate 2,000 volts, and leave the increase of 200 volts to be brought about by the action of the field.

3. Since the speed and frequency are fixed, the number of poles is also fixed by the relation

$$n = \frac{p}{2} \times s$$

where s = revolutions per second;
p = number of poles;
n = frequency.

We then have

$$60 = \frac{p}{2} \times \frac{600}{60}$$

$$p = 12$$

and the machine must be provided with twelve poles to give the required frequency at a speed of 600 R. P. M. We might have used a speed of 900 R. P. M. and eight poles, the frequency being the same in either case. It is better, however, to use the lower speed (600 R. P. M.) for a machine of this capacity, so we will adopt the twelve pole 600 R. P. M. design. The field will be external to the armature, and will be provided with twelve equally spaced poles projecting radially inwards. We will also follow the usual practice and make the distance between the poles equal to the width of the pole face, or, in other words, make the width of pole face equal to one-half the pitch. The pole pieces will, therefore, cover one-half the surface of the armature.

DIMENSIONS OF CONDUCTOR AND CORE

4. The current output at full load will be

$$I = \frac{\text{watts}}{\text{full-load voltage}} = \frac{\text{kilowatts} \times 1{,}000}{E'} \qquad \textbf{(1)}$$

$$= \frac{100 \times 1{,}000}{2{,}200} = 45.4 \text{ amperes}$$

The machine must therefore be capable of delivering a current of at least 45.4 amperes continuously without the temperature rise above the surrounding air exceeding 40° C.

5. The cross-section of the conductor that is used on the armature is determined by the current that it must carry, and this in turn depends on the way in which the different armature coils are connected up. Since the armature under consideration must generate a high voltage, we will use an open-circuit winding and connect all the armature coils in series. The current flowing through the armature conductor at full load will then be the same as the full-load current output of the machine, that is, 45.4 amperes. The student should compare this with the calculations determining the size of wire used on a continuous-current armature. It will be seen that in this latter case the current in the armature conductor was less than the total current output of the machine depending on the number of paths in the winding. In some of the older types of alternators, the armature conductors were worked at a high current density, in some cases less than 300 circular mils per ampere being allowed. For machines of good design, the number of circular mils per ampere usually lie between 500 and 700. For a trial value, take 550 circular mils per ampere in order to determine the approximate necessary cross-section of the conductor.

Let

A = area of cross-section of conductor in circular mils;
I = current in conductor;
m = circular mils per ampere.

Then,

$$A = Im \qquad (2)$$

In this case $I = 45.4$ and $m = 550$. Therefore, the cross-section of the conductor will be

$$45.4 \times 550 = 24{,}970 \text{ circular mils}$$

A No. 6 B. & S. wire would give 26,250 circular mils, which is quite near to the cross-section required, or two No. 9 wires in parallel would give a cross-section of 26,180 circular mils. Two bare No. 9 wires covered with a double wrapping of cotton should be used, because the two wires in multiple will give a more flexible and easily wound conductor. The double thickness of this covering will be about 15 mils. The diameter of No. 9 wire is .114 inch; hence, the width of the conductor over all will be .243 inch and the thickness .129 inch. Fig. 1 shows a cross-section of the conductor, illustrating the arrangement of the insulation.

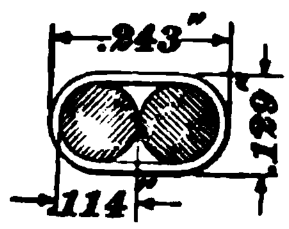


FIG. 1

DESIGN OF ARMATURE CORE

6. The diameter of the armature is determined by the speed of rotation and the allowable safe value of the peripheral speed. A safe peripheral speed for a belt-driven machine of this type may be taken at about 5,000 feet per minute. Hence, the diameter of armature in inches equals

$$d_a = \frac{\text{peripheral speed} \times 12}{\text{R. P. M.} \times \pi} \qquad (3)$$

$$= \frac{5{,}000 \times 12}{600 \times \pi} = 31.8 \text{ inches}$$

We will therefore adopt $31\frac{3}{4}$ inches = 31.75 as the outside diameter of the armature core.

7. The length of the armature core parallel to the shaft, or the spread of the laminations, must be large enough

to enable the armature to present sufficient radiating surface to get rid of the heat generated. In other words, the armature must be large enough to do the work required of it without overheating. The core losses and I^2R loss of the machine under consideration cannot be determined exactly until the dimensions of the armature have been determined. The curve shown in Fig. 1, Part 1, gives the relation between the output and I^2R loss for machines of good design, and it is seen that for a machine of 100-kilowatt capacity, the I^2R loss should be about 1.95 per cent. of the output. The approximate I^2R loss may then be taken as $100{,}000 \times .0195 = 1{,}950$ watts.

8. This armature is of rather large diameter and runs at a fairly high peripheral speed. Good ventilation should easily be obtained by constructing the spider to allow free access of air and by providing the core with ventilating ducts. With such an armature there should be no difficulty in radiating about 2.8 watts for each square inch of core surface with a rise in temperature of 40° C. The core losses are apt to be quite large; hence, to be on the safe side, we will allow half this radiation capacity for the core losses and half for the I^2R loss. This means that we should have about $\frac{1}{1.4}$ square inch of cylindrical surface for each watt I^2R loss. This would call for a surface of $1{,}950 \times .7 = 1{,}365.0$ square inches.

9. The outside circumference of the armature is $31.75 \times \pi = 100$ inches, nearly; hence, the approximate length of armature core parallel to the shaft should be about 13.65 inches. As a basis for further calculation, we will adopt a trial length of core of say 14 inches. It may be found necessary to modify this dimension slightly, as the design is worked out further, but it should not be made much less than this, or there will be danger of the armature overheating.

10. We have now determined the approximate dimensions of the armature core, and are in a position to calculate

the magnetic flux Φ after we have decided on the density to be used in the air gap. This machine will be provided with wrought-iron pole pieces; hence, we may take 40,000 lines per square inch as a fair value for the magnetic density in the air gap. The total magnetic flux Φ from one pole will be the area covered by the pole multiplied by the magnetic density. The poles cover one-half the circumference; hence, the length of arc on the armature covered by each pole will be

$$\frac{\pi \times d_a \times .5}{\text{number of poles}} \qquad (4)$$

$$= \frac{3.14 \times 31.75 \times .5}{12} = 4.16 \text{ inches}$$

The length of the pole face is the same as the length of the armature core, i. e., 14 inches; hence, the area of the pole face is $14 \times 4.16 = 58.2$ square inches.

The total flux from each pole will therefore be $58.2 \times 40,000 = 2,328,000$ lines.

11. Since the flux Φ, the frequency n, and the E. M. F. E generated at no load are now known, the number of turns T necessary to generate the voltage E can be calculated. This armature will be provided with six coils or twelve slots, that is, one slot for each pole; consequently, all the conductors may be considered active at once, and we may use the formula

$$E = \frac{4.44\, \Phi\, T n}{10^8}$$

or

$$T = \frac{E \times 10^8}{4.44 \times \Phi \times n} \qquad (5)$$

The voltage to be generated at no load is 2,000, the frequency is 60, and the flux Φ is 2,328,000; hence, we have

$$T = \frac{2,000 \times 100,000,000}{4.44 \times 2,328,000 \times 60} = 322$$

12. From the above, it is seen that we must place as nearly 322 turns on the armature as possible. There are

twelve slots, or six coils; hence, there would be $\frac{322}{6} = 53.6$ turns per coil and 53.6 conductors in each slot. This number would not be practicable, since we should arrange the coils so that they will wind up into a number of layers without any fractions of turns. We must therefore arrange the coils to give the required number of turns as nearly as possible, and then modify the length of the turns, so that the voltage generated will not be altered. Suppose we arrange the coil and slot as shown in Fig. 2, using 8 turns of the twin conductor in each layer, and having 7 layers per coil. This will give 56 turns per coil and 56 conductors per slot.

FIG. 2

13. The dimensions of the slot may now be determined from the known number of conductors that are to be placed in it, and the necessary space that must be allowed for insulation. We will allow .06 inch or 60 mils all around for the paper and mica tube that composes the slot insulation, and .04 inch or 40 mils for lapping around the coil. In addition to this, we will allow for six layers of insulation, 10 mils thick, between the layers of the coil. This will make the necessary width of the slot $7 \times .129 + 6 \times .01 + 2 \times .04 + 2 \times .06 = 1.163$ inches. The necessary depth of slot will be $8 \times .243 + 2 \times .04 + 2 \times .06 = 2.144$ inches.

In order to be sure that the coil will slip into the slot without having to be forced, and also to compensate for any slight roughness, we will adopt the dimensions shown in Fig. 2, namely, $1\frac{3}{16}$ inches wide by $2\frac{5}{32}$ inches deep. We will make the wooden wedge $\frac{1}{4}$ inch thick, and the opening at the circumference the same width as the slot, in order to allow the coil to be slipped easily into place.

14. In order to obtain an even number of turns per coil, the total number of turns has been increased from 322, as first calculated, to 336. It follows, therefore, that if the dimensions of the armature are not altered in any way to

compensate for this increase in the number of conductors, the machine would give more than 2,000 volts when run at a speed of 600 revolutions per minute. In order, therefore, to keep the voltage generated the same, each conductor must be shortened a small amount, so that the poles and armature core will also be shortened. This will reduce the flux Φ, so that the voltage generated by the 336 conductors will be 2,000 volts. The final length of armature may be obtained as follows:

We have
$$\Phi = \frac{E \times 10^8}{4.44 \times Tn} \tag{6}$$

and in this case

$$\Phi = \frac{2{,}000 \times 100{,}000{,}000}{4.44 \times 336 \times 60} = 2{,}235{,}000, \text{ nearly}$$

That is, in order to keep the voltage the same, the flux is reduced from 2,328,000 to 2,235,000.

The area per pole will then be

$$\frac{\Phi}{\text{air-gap density}} = \frac{2{,}235{,}000}{40{,}000} = 55.8 \text{ square inches} \tag{7}$$

and the length of the pole and armature core parallel to the shaft will be

$$\frac{\text{area}}{\text{polar arc}} = \frac{55.8}{4.16} = 13.42 \text{ inches} \tag{8}$$

It will thus be noticed that the armature core is shortened slightly, thus shortening up each conductor and making the length of active wire the same with the 336 conductors as it would have been if 322 had been used. We will therefore take $13\frac{7}{16}$ inches as the final value for the length of the core parallel to the shaft (see l_a, Fig. 3).

15. All the essential dimensions of the armature core have now been determined except the diameter of the hole in the disks. This inner diameter of the core is determined by the cross-section of iron that must be provided to carry the magnetic flux through the armature core from one pole to the next, and this cross-section in turn depends on the density at which the core is worked.

Fig. 3 shows a cross-section of the core, and Fig. 4 shows a portion of the armature lying between two pole pieces. In order to determine the inside diameter, we must first obtain the distance d_c, or the depth of the iron below the bottom of the slots. The lines of force flow from the north to the south pole, as shown in the figure, and it will be seen that the number of lines flowing through the portion *a b* under a slot is one-half the total number flowing from the pole

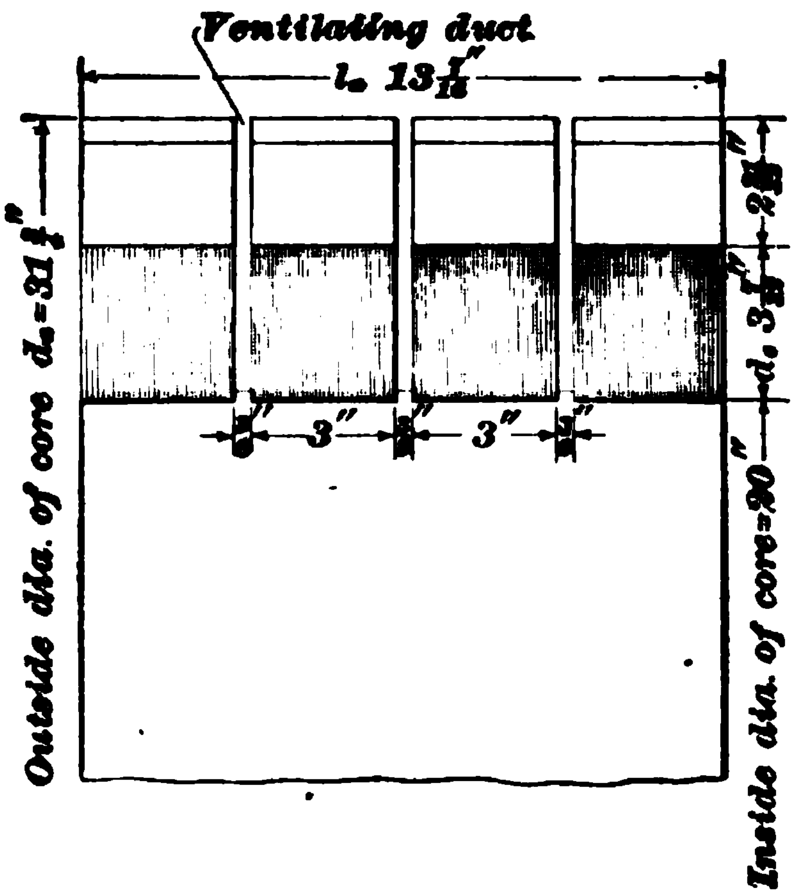


FIG. 3

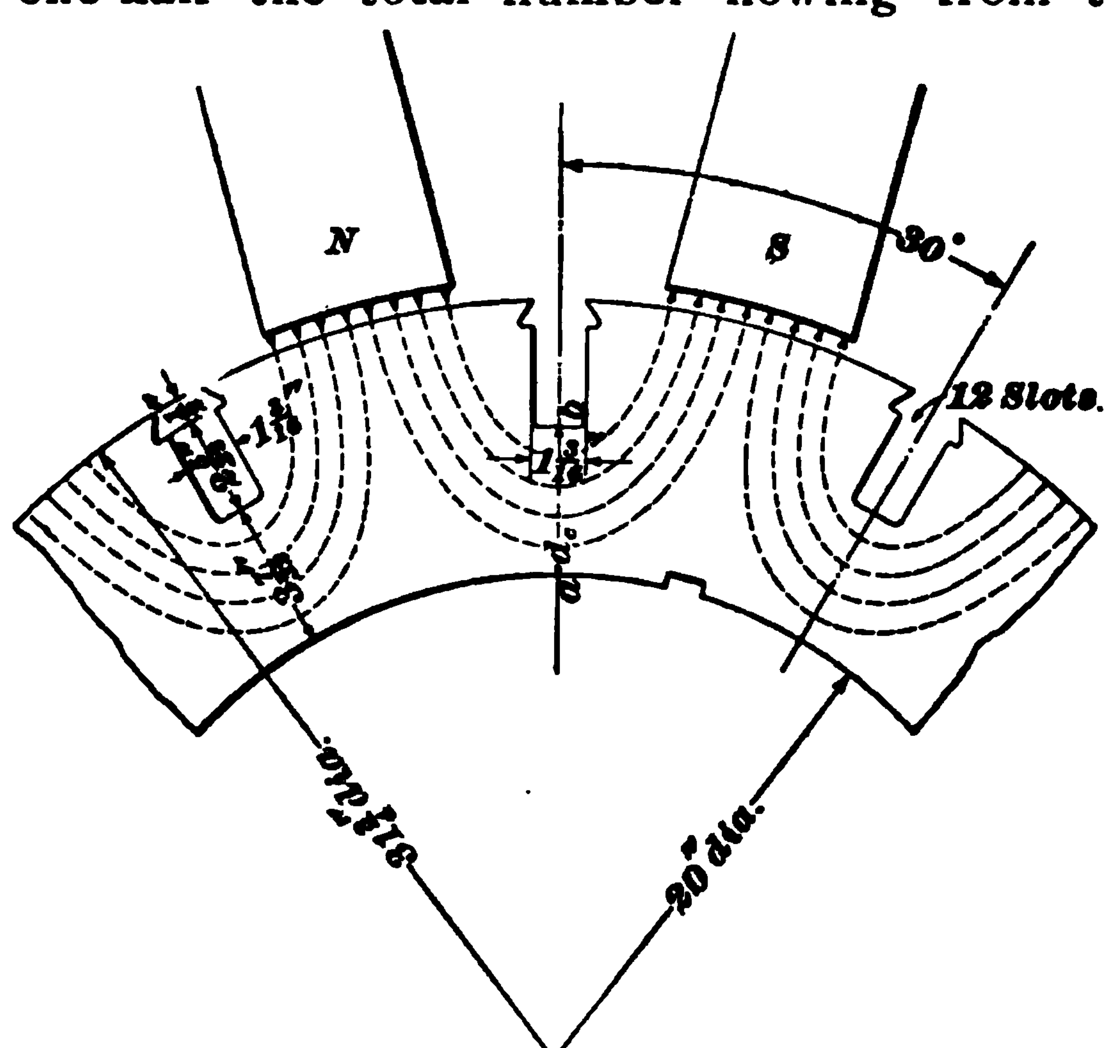


FIG. 4

piece. Hence, the flux through the armature core is $\frac{1}{2}\Phi$. The area of cross-section of iron required will then be

$$A_c = \frac{\frac{1}{2}\Phi}{\mathbf{B}_c} \qquad (9)$$

where $\mathbf{B}_c$ is the magnetic density at which the core is worked. We will take the value of $\mathbf{B}_c$ as 30,000 lines per square inch. This will make

$$A_c = \tfrac{1}{2} \times \frac{2,235,000}{30,000} = 37.25 \text{ square inches}$$

This is the area of cross-section of iron, and it is equal to the radial depth of the core under the slots (*a b*, Fig. 4) multiplied by that length of core parallel to the shaft which is actually occupied by iron. The over-all length of the core parallel to the shaft is $13\frac{7}{16}$ inches, but part of this is taken up by the varnish, or other insulation, between the disks, as well as the portion taken up by the air ducts. In the present case, we will provide the armature with three air ducts, each $\frac{3}{8}$ inch wide, as shown in Fig. 3, the disks being spaced apart this distance by suitable ribbed brass castings, or by a special spacing disk. These three ducts will therefore occupy a linear distance of $1\frac{1}{8}$ inches, leaving $13\frac{7}{16} - 1\frac{1}{8}$, or $12\frac{5}{16}$ inches to be occupied by the iron and insulation on the disks. We will take $11\frac{1}{2}$ inches as the actual length of iron, the disks being insulated by having a thin coating of japan placed on every other disk. The required radial depth will then be $\frac{37.25}{11.5} = 3.23$ inches. We will therefore make the depth of iron $3\frac{7}{32}$ inches. (See Figs. 3 and 4.) The total depth of the slot is $2\frac{21}{32}$ inches; hence, the total radial depth of the disk is $2\frac{21}{32} + 3\frac{7}{32} = 5\frac{7}{8}$ inches, and the inside diameter is $31\frac{3}{4} - 2 \times 5\frac{7}{8} = 20$ inches. The dimensions of the disk are, therefore, as shown in Fig. 4. There are twelve slots of the dimensions shown in Fig. 2, these slots being spaced equally 30° apart.

CALCULATION OF ARMATURE LOSSES

16. The dimensions of the armature having been determined, it is now necessary to calculate the losses to see if the armature will deliver the required output without the losses exceeding the allowable amount. We will first calculate the $I^2 R$ loss.

17. The resistance of the armature can be determined quite closely, since the length of wire on it can be estimated and the cross-section is already known. The length of wire can be obtained by laying out one of the coils to scale and measuring up the mean length of a turn. The coil must bridge over the distance from the center of a north pole to that of a south pole, and the ends of the coil must be rounded out so as to clear the armature core. The coil will be

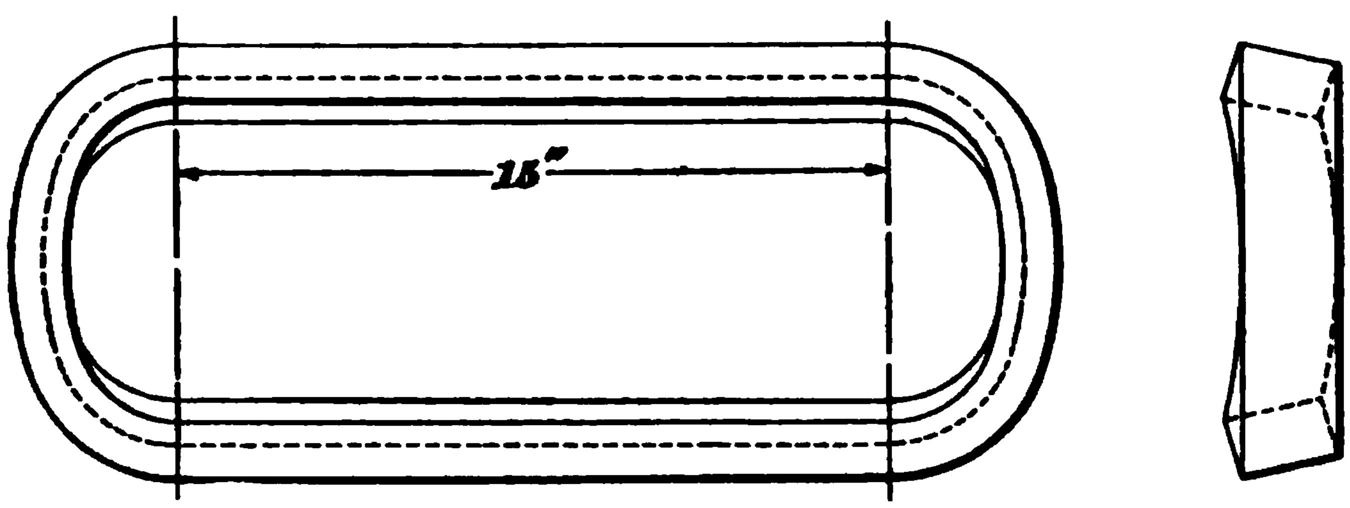


FIG. 5

shaped as shown in Fig. 5. The straight portion of the coil will be made 15 inches long, in order to allow the coil to project about $\frac{3}{4}$ inch from the slots at each end before it begins to turn. The mean turn, shown dotted, is the turn through the center of the coil. Its length is readily determined from the drawing; in this case it is about 54 inches. The total length of conductor on the armature will therefore be $54 \times 336 = 18,144$ inches, or 1,512 feet.

18. The hot resistance of any known length of a conductor may be found as follows:

$$R = \frac{\text{length of wire in inches}}{\text{area in circular mils}}$$

Applying this to the armature just worked out, we find

$$(\text{hot})\ R = \frac{18,144}{26,180} = .693 \text{ ohm}$$

We will take the resistance as .7 ohm, in order to make some allowance for the resistance of the connections between the coils.

19. The full-load current is 45.4 amperes; hence, the $I^2 R$ loss at full load will be $(45.4)^2 \times .7 = 1,442$ watts. This shows that the $I^2 R$ loss is well under the limit of 1,950 watts and that the armature would be capable of delivering a little over 45.4 amperes without the $I^2 R$ loss exceeding the allowable amount. The outer cylindrical surface of the armature as obtained from the final dimensions is $\pi \times 31\frac{3}{4} \times 13\frac{7}{16} = 1,343$ square inches, nearly, which allows a little over .9 square inch per watt $I^2 R$ loss, which should be an ample allowance for an armature of this type.

20. The hysteresis loss may be calculated when the volume of iron, magnetic quality of the iron, and frequency are known. The area of the end of the core is $\frac{1}{4} \pi (31.75^2 - 20^2) = 477.3$ square inches, nearly.

The area of each slot is about 3.4 square inches, and the total area taken out by the slots 40.8 square inches, leaving 436.5 square inches as the area of the disks. The actual length of iron parallel to the shaft is $11\frac{1}{2}$ inches; hence, the volume of iron in the core is $436.5 \times 11.5 = 5,020$ cubic inches.

The magnetic density in the core is 30,000 lines per square inch. Referring to curve *B*, Fig. 2, Part 1, we find that for a density of 30,000 the loss per cubic inch per 100 cycles is .42 watt. Hence, the hysteresis loss in watts is

$$W_H = \frac{5,020 \times .42 \times 60}{100} = 1,265$$

21. The eddy-current loss is not easily obtained, but the combined core losses in this case would likely be fully as great as, if not greater than, the $I^2 R$ loss of 1,442 watts. If the combined losses were, say, 3,000 watts, the electrical efficiency at full load would probably be in the neighborhood of 94 or 95 per cent., as there would be about 2 per cent. loss in the field and various connections. The commercial efficiency would be somewhat less than this on account of the bearing friction, brush friction, etc.

ARMATURE WINDING FOR TWO-PHASE ALTERNATOR

22. The armature just worked out has been designed to deliver a single current at 2,000 volts pressure. Suppose it were desired to provide this armature, or rather an armature of the same general dimensions, with a winding that would deliver two currents at 2,000 volts pressure, and differing in phase by 90°. We could use two windings, each consisting of six coils connected in series, the two sets being displaced 90° from each other with regard to the poles. The total output, as before, is to be 100 kilowatts; hence, the output per phase will be 50 kilowatts, and the current in each phase at full load will be $\frac{50 \times 1,000}{2,200} = 22.7$ amperes. The current in the armature conductor is, therefore, one-half of that in the single-phase machine, and, using the same current density, we may make the conductor of a single No. 9 wire instead of two in multiple.

23. The voltage generated in each phase is to be 2,000. The total magnetic flux is the same, since the size of the pole pieces and armature is not altered; hence, the number of conductors in each phase must be 336. Each coil on the two-phase armature will therefore consist of 56 turns of No. 9 B. & S. wire, provided we can arrange this number satisfactorily in the slot. If we use 7 layers with 8 turns per layer, we will have a slot of the same width as before, but only a little over half as deep. This will result in a slot that is not very deep compared with its width, whereas it is generally better to have the slot considerably greater in depth than in width. It will give a much better proportioned slot if we use only 5 layers, and place 11 turns in each layer, or 55 turns per

FIG. 6

coil instead of 56. This will lower the voltage slightly, but will leave the dimensions of the core the same, and compensate for this slight decrease by strengthening the field a small amount. In other words, we will compensate for the decrease in the number of turns by increasing Φ so that E will remain the same. The slot may then be arranged as shown in Fig. 6. Allowing the same amount for insulation as before, the width of the slot will be equal to $5 \times .129 + 4 \times .01 + 2 \times .04 + 2 \times .06 = .885$ inch. The depth of the slot will be $11 \times .129 + 2 \times .04 + 2 \times .06 = 1.619$ inches.

We will therefore make the slot $\frac{11}{16}$ inch wide and $1\frac{5}{8}$ inches deep. As this coil is lighter than the one used for the single-phase armature, we will allow only $\frac{3}{8}$ inch for the wooden wedge, and make the upper part of the slot as shown in Fig. 6. We will leave the inner diameter of the disk the same, the cross-section of iron being slightly greater than before, on account of the smaller depth of the slots. The disk for this two-phase armature will then be of the dimensions shown in Fig. 7. In this case the disk is provided with 24 slots of the dimensions shown in Fig. 6, there being 12 slots for each phase.

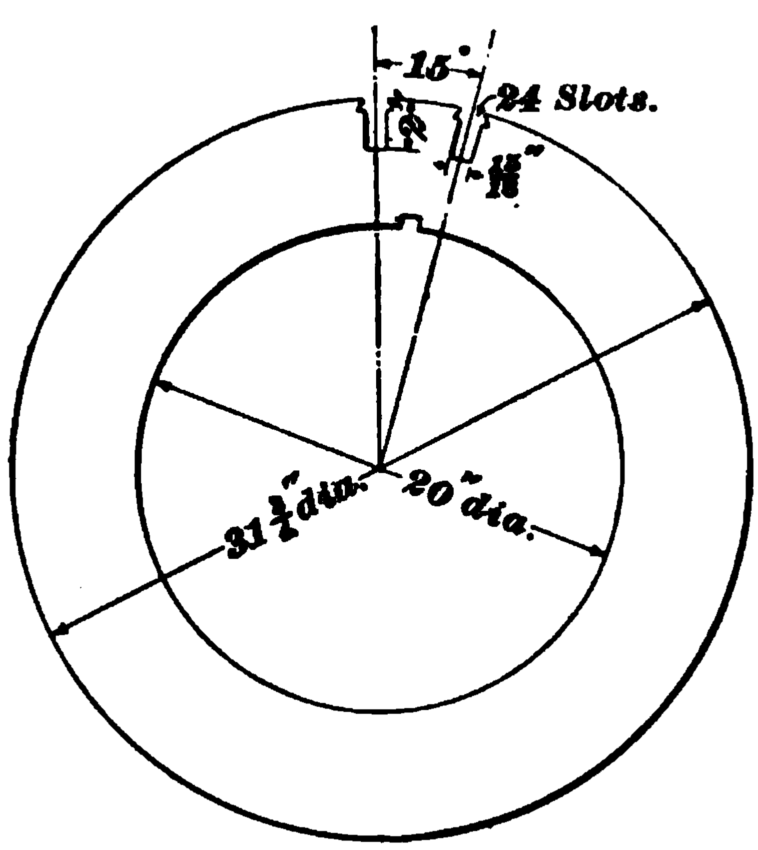


FIG. 7

24. The $I^2 R$ loss in this armature would be practically the same as that in the single-phase armature previously calculated. The resistance of each phase will be about double the resistance of the single-phase armature, because in each phase there is about the same length of wire as before, but this wire has only one-half the cross-section of that used for the single-phase machine. We may, therefore, take the resistance per phase as $2 \times .7$ or 1.4 ohms. The $I^2 R$ loss per phase will be $(22.7)^2 \times 1.4 = 721$ watts, and the total loss in the two

phases will be 1,442 watts, as before. The radiating surface has not been altered in any way, so that the two-phase armature should deliver its output without overheating. The core losses will also be about the same, because the volume of the core and the magnetic density have not been altered materially.

ARMATURE WINDING FOR THREE-PHASE ALTERNATOR

25. Suppose it were desired to wind the above armature so that it would deliver 100 kilowatts to a system by means of three currents differing in phase by 120°. It would be necessary to supply the armature in this case with three sets of coils displaced from one another 120° with regard to the poles. Each set would consist of six coils connected in series, the three groups being connected together according to either the **Y** or Δ method and the terminals led to the collector rings. In this case it will be supposed that the **Y** method of connection is used, because the current in each phase is small and the line voltage high. By adopting the **Y** method, the voltage to be generated per phase is reduced, thus calling for a smaller number of turns per coil than would be required if the armature were Δ connected. The total output, as before, is to be 100 kilowatts, and the line pressure at full load, 2,200 volts. We have, for a three-phase machine,

$$\text{watts output} = \sqrt{3}\,E\,I$$

where I is the full-load line current, and E the voltage between the lines at full load. For the present case, we have, therefore, $100{,}000 = \sqrt{3}\,I\,2{,}200$,

or $$I = \frac{100{,}000}{2{,}200\sqrt{3}} = 26.2 \text{ amperes}$$

26. If the line current at full load is 26.2 amperes, the full-load current in the armature conductors must also be

26.2 amperes, because, in a Y-connected armature, the current in each phase is the same as the line current. We will allow 550 circular mils per ampere, as before, to get an approximate estimate of the area of cross-section of conductor required. This gives $550 \times 26.2 = 14,410$ circular mils.

No. 9 wire has a cross-section of 13,090 circular mils, while No. 8 has a cross-section of 16,510 circular mils. We will use the No. 8 wire, since it is on the large side, and will thus tend to make the $I^2 R$ loss less. The diameter of this wire when covered with a double wrapping of cotton will be about .14 inch.

27. The line voltage at no load is to be 2,000; consequently, the voltage generated in each phase will be $\frac{2,000}{\sqrt{3}}$ $= 1,154$ volts, because the armature is Y connected. We have

$$E = \frac{4.44\, \Phi\, T n}{10^8} \times k$$

where E is the voltage at no load generated in each phase. In this case, the constant k is 1, because we are using a concentrated winding, there being only one slot for each pole and phase. T is the number of turns in each phase. The magnetic flux Φ will be considered the same as before, because the dimensions of the pole pieces and armature have not been altered. We then have

$$T = \frac{E \times 10^8}{4.44 \times \Phi \times n}$$

or $$T = \frac{1,154 \times 10^8}{4.44 \times 2,235,000 \times 60} = 194 \text{ turns, nearly}$$

These 194 turns are to be split up into the six coils constituting one phase. We can use 32 turns per coil, and thus have 192 turns in each phase instead of 194. This slight decrease in the number of turns could be compensated for by increasing the field strength slightly. The three-phase

armature will therefore be provided with 18 coils, each consisting of 32 turns of No. 8 wire. These coils are to be divided into three sets of six coils, each of the three sets being connected up Y.

28. The arrangement of the slot that would probably be best adapted to this number of turns would be four layers with eight turns per layer, as shown in Fig. 8. We will allow the same thickness of insulation as in the previous examples, thus making the width of the slot $4 \times .14 + 3 \times .01 + 2 \times .04 + 2 \times .06 = .79$ inch. The depth of the slot will be $8 \times .14 + 2 \times .04 + 2 \times .06 = 1.32$ inches.

FIG. 8

We will therefore adopt the dimensions $\frac{13}{16}$ inch by $1\frac{5}{16}$ inches as the width and depth, and make the wedge $\frac{3}{8}$ inch thick, as in the last case. Fig. 9 shows the dimensions of the disk for this machine. It is provided with 36 slots, equally spaced and of the dimensions shown in Fig. 8. The other dimensions of the disk remain the same as for those previously calculated.

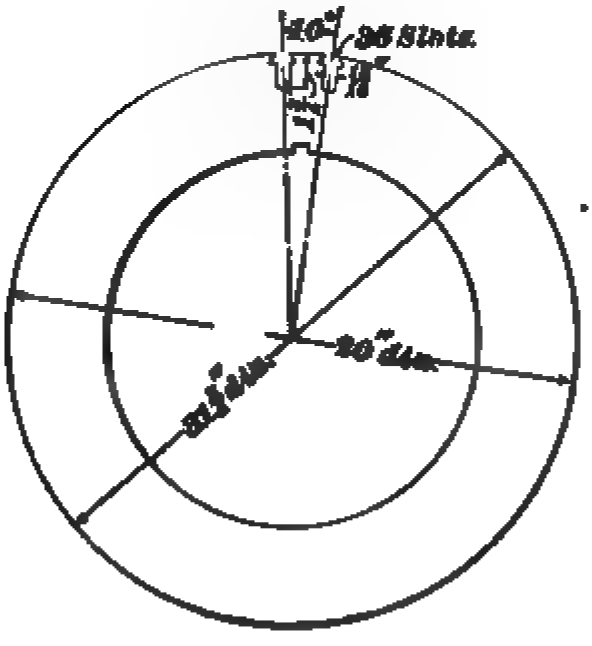


FIG. 9

29. The $I^2 R$ loss for this armature should not differ greatly from the loss calculated for the other two. We can easily make an approximate estimate of the $I^2 R$ loss in such a three-phase armature as follows: The mean length of a turn will be very nearly the same as that obtained for the single-phase machine, because the angular distance that the coils span remains the same and the length of the armature core has not been

altered. There might possibly be a slight increase in the length, owing to the shape that must be given to the ends of some of the coils in order to allow them to pass each other at the ends of the armature, but it will be sufficiently accurate to take the length of a turn the same as before, namely, 54 inches, for the present purpose. The total length of conductor in each phase will be $54 \times 192 = 10,368$ inches. The hot resistance of each phase will therefore be

$$\frac{10,368}{16,510} = .628 \text{ ohm}$$

The current in each phase at full load is 26.2 amperes. Hence the I^2R loss in each phase will be $(26.2)^2 \times .628 = 431$ watts, approximately. We will take the loss in each phase at, say, 500 watts, in order to allow for the loss due to the resistance of the connections. The total loss in the armature would therefore be 1,500 watts, or about the same as for the other armatures. The radiating surface is the same as in the other two cases, so that this armature should deliver 100 kilowatts within the specified temperature limit. The core losses, as before, would remain nearly the same, since the volume of iron has not been changed appreciably. The coils of the two-phase and three-phase armatures would, if anything, run cooler than those of the single-phase machine, because the coils are lighter and the heating effect is distributed among a larger number of coils.

30. The three-phase armature might have been designed for a Δ winding, in which case each phase would be provided with a sufficient number of turns to generate 2,000 volts. The current in the conductor would, however, be only $\frac{26.2}{\sqrt{3}}$, or 15.1 amperes; so that, while the number of turns must be increased, the cross-section of the conductor may be decreased in the same ratio, and the size of armature slot will be about the same in either case.

31. The above calculations for single-, two-, and three-phase armatures have all been made on the supposition that

unicoil, or concentrated, windings were used. The method of designing the armature when distributed windings are used is, in general, the same, with the exception that the formula giving the relation between the E. M. F., flux, and turns must be modified to suit the style of armature winding used. The effect of using distributed windings has already been pointed out, and calculations relating to such windings will be given in connection with induction-motor design.

COMPLETED ARMATURES

32. Fig. 10 shows a finished armature with collector rings. This armature has a concentrated winding, as indicated by the small number of large slots around its circumference. The wooden wedges for holding the coils in place are shown at *w*: *c* are the ventilating ducts for allowing a circulation of air through the core. The cast-brass shields *s*

FIG. 10

are supported from the armature spider, and are used to protect the projecting ends of the coils. The armature is shown complete with the collector rings *r* and the rectifier *t*. Fig. 11 shows a large three-phase armature with a distributed winding. It will be noticed that this armature has a large number of narrow slots and is similar in appearance to a continuous-current armature, except for the absence of the commutator and its connections. The ends of the bars rest

on the spider flanges and are held down by the bands *a*. The disks are carried by the spider *b* and are clamped up by the end plates *c*. The copper bars *d*, *d* are the connections between the winding and the collector rings. It will be

FIG 11

noticed that this armature is not provided with a rectifier, because this style of armature is of such low inductance that the machine can be made to regulate closely enough without the use of a set of series-coils on the field.

DESIGN OF FIELD MAGNETS

33. Stationary field magnets for alternators are generally constructed in about the same way as those for multipolar continuous-current machines, the main difference being the large number of poles with which an alternator field is usually provided. The design almost universally adopted for stationary fields consists of a circular yoke *a*, usually of cast iron (see Fig. 12), provided with a number of poles *d* projecting radially inwards toward the armature. The field is usually made in halves, so that the upper part *a* may be removed to give access to the armature. The lower half *b* is very often cast with the base of the machine, especially in machines of moderate size. In larger machines

the lower half is cast separately and provided with projections *c*, *c*, by means of which it is bolted to the bed. The halves are held together by means of the bolts *e*. Some

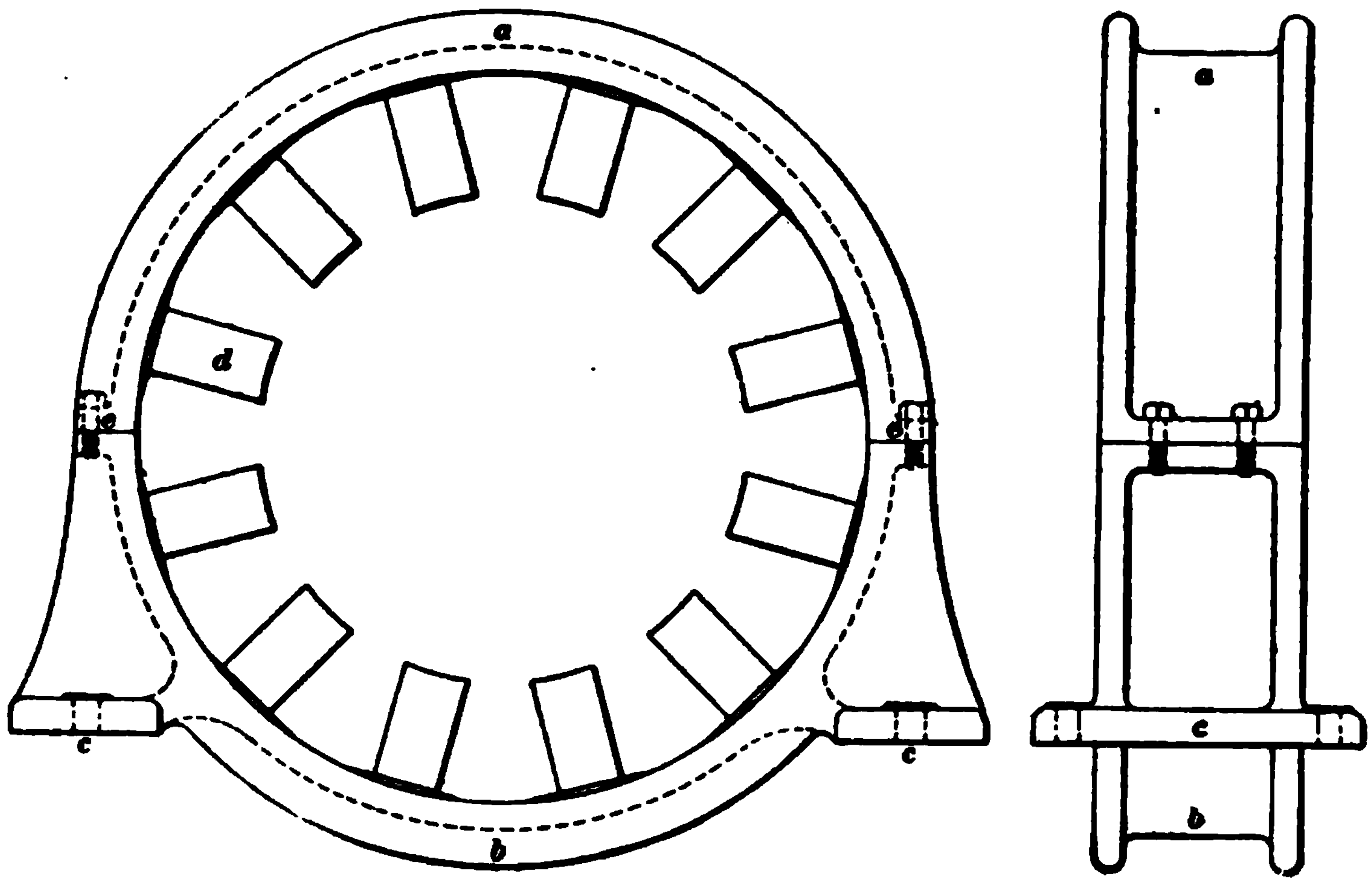


FIG. 12

makers build fields of this description, which are divided on the vertical diameter, allowing the halves to be separated sidewise in order to get at the armature. In some small machines the yoke is made in one piece, and the machine is so arranged that the armature may be drawn out endwise.

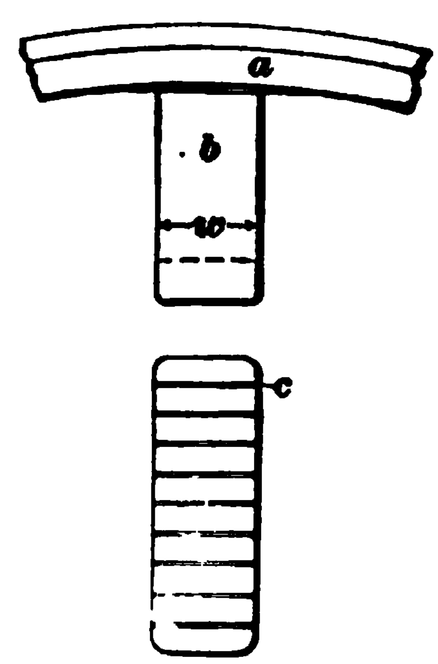


FIG. 13

34. The pole pieces used with these stationary fields are usually straight; that is, they are not provided with pole shoes or polar projections of any kind. Pole shoes are not necessary, because the length of the polar arc is generally small. Some of the older types of machines were provided with cast-iron pole pieces cast with the yoke, but most modern machines have wrought-iron pole pieces built up out of plates and cast welded into the yoke. Fig. 13 shows a form of cast-iron pole piece that was used on some of the older machines. This is a straight pole piece *b* cast with the yoke *a*. In order to prevent

eddy currents being set up in the pole pieces by the changes of magnetism in the pole face due to the coarse teeth and slots of the armature sweeping past it, the surface of the pole is broken up by a number of thin U-shaped pieces of sheet iron *c* cast into the pole. This limits the paths in which the eddy currents flow, and thus cuts down the heating of the poles due to them. Cast-iron poles cannot be worked at a magnetic density much over 30,000 or 35,000 lines per square inch, and there is always more or less loss in the polar surface due to eddy currents. In order, therefore, to do away with this eddy-current loss and to permit the use of a higher magnetic density, laminated wrought-iron pole pieces have come largely into use, and are employed on nearly all modern alternators. Fig. 14 shows a common form of this type of pole. The pole is built up of soft iron stampings *b*, which are clamped together between the end plates *d*, *d* by means of the bolts *c*, *c*. This built-up pole piece is cast into the yoke *a*. The plates used for these poles are usually from $\frac{1}{16}$ inch to $\frac{1}{8}$ inch in thickness. If the bolt at the inner end of the pole piece is very near the end of the pole, it should be lightly insulated by a paper tube; otherwise it may, by short-circuiting the plates, allow eddy currents to flow. The length of these pole pieces parallel to the shaft is made equal to the corresponding length of the armature core. The breadth of the pole *w* is determined by the polar arc that the pole must span. It will be noticed that the cross-section of these pole pieces is, in general, rectangular, or nearly so, and the field coils are therefore nearly rectangular. Circular field coils and field cores, which are so common with direct-current machines, are seldom met with on alternators, because the width of the pole *w* is generally small compared with the length of the armature, except perhaps on large slow-speed machines.

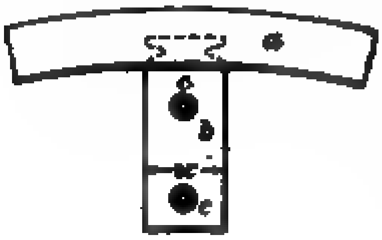


FIG. 14

35. The yoke *a b*, Fig. 12, is nearly always made of cast iron. The magnetic flux through the yoke of an alternator is usually small, and as the yoke must have considerable cross-section to make it strong enough, mechanically in any event, there is no object in using cast steel to make the cross-section small, as is frequently done in the case of direct-current machines. Usually, the yoke is worked at a low density in order to give sufficient cross-section to make it strong enough mechanically. The shape of the cross-section is largely a matter of design, so long as the requisite area of iron is provided. Fig. 15 (*a*) shows a plain rectangular section with rounded corners; (*b*) shows a section that is frequently used, the well-rounded corners and the elliptical back giving the yoke a more graceful appearance than the plain rectangular section. Fig. 15 (*c*) shows a section that is commonly used. In this case the yoke is provided with flanges that make it stiff and that also give the yoke a solid appearance, although the cross-section of metal in it may be quite small (see Fig. 12). Fig. 15 (*d*) shows a flanged construction with the flanges moved in from the edge of the yoke. The breadth of the yoke is usually somewhat greater than the length of the pole pieces parallel to the shaft, so that the yoke will partially cover the ends of the field coils.

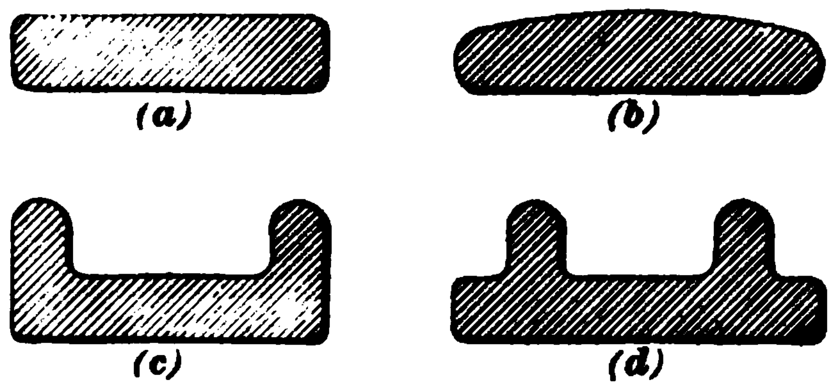


FIG. 15

REVOLVING FIELDS

36. A number of different constructions are used for **revolving fields,** depending on the methods adopted for furnishing the field excitation. A common type is that in which the radial pole pieces are bolted to a cast-steel rim, each pole piece being provided with an exciting coil, as in the case of the stationary field just described. Fig. 16

shows a pole piece and coil for this type of field. The pole *a* is built up out of sheet-iron plates and secured by the stud *d* to the rim *b*, which is carried on the spokes of the field spider. Stud *d* screws into the bar *c* that passes through openings in the stampings, and the projections on the pole

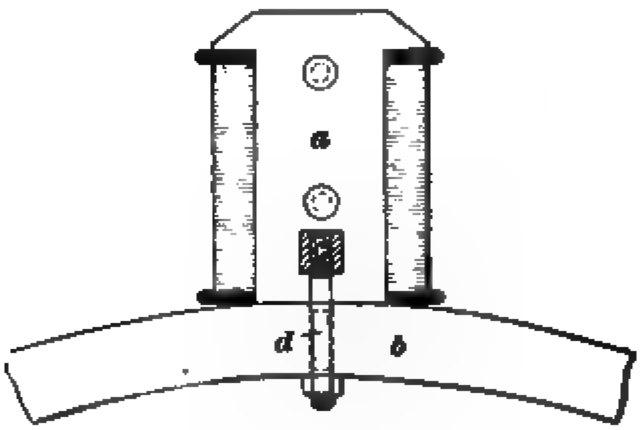


FIG. 16

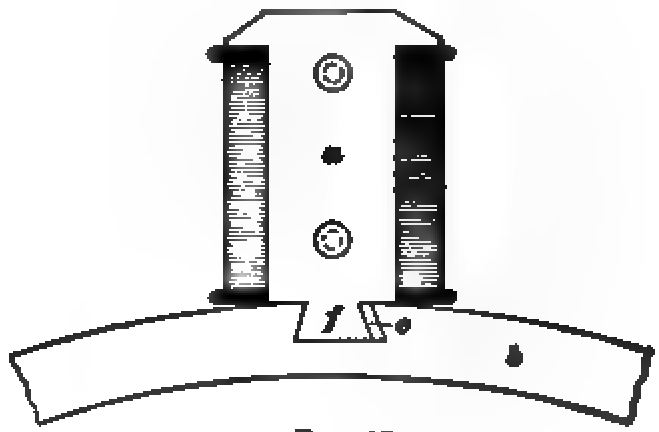


FIG. 17

serve to hold the coil in place. In some cases the poles are made straight and the coil held in place by projecting lugs on the end clamping plates. Fig. 17 shows a similar pole piece, the plates in this case being dovetailed into the field ring and held firmly in place by a key *e* driven in at one side.

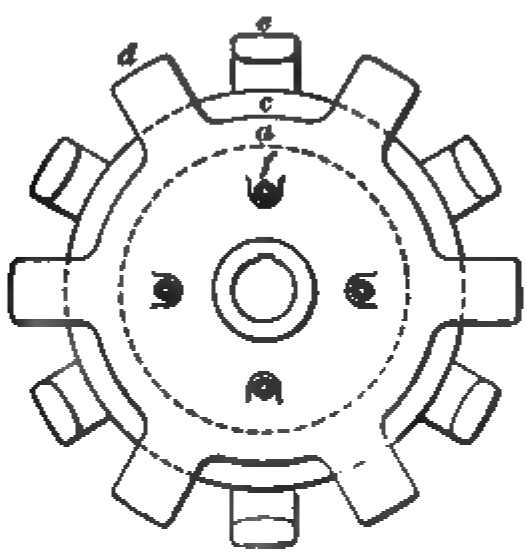


FIG. 18

37. Revolving fields have been built so as to require only one exciting coil for all the poles. A field of this type is shown in Fig. 18 The exciting coil *c* is circular. The field casting is in two parts *a* and *b*, held together by bolts *f*,

and each casting has a crown of six poles, as shown. When current is sent through the coil, lines of force thread through it; all the projections *d* attached to one side being, say, north poles, and all those attached to the other side, south poles. This construction gives rise to large magnetic leakage, and is now seldom used.

FIELD-MAGNET COILS

38. Field-magnet coils may be wound on spools constructed similar to those used for the field coils for continuous-

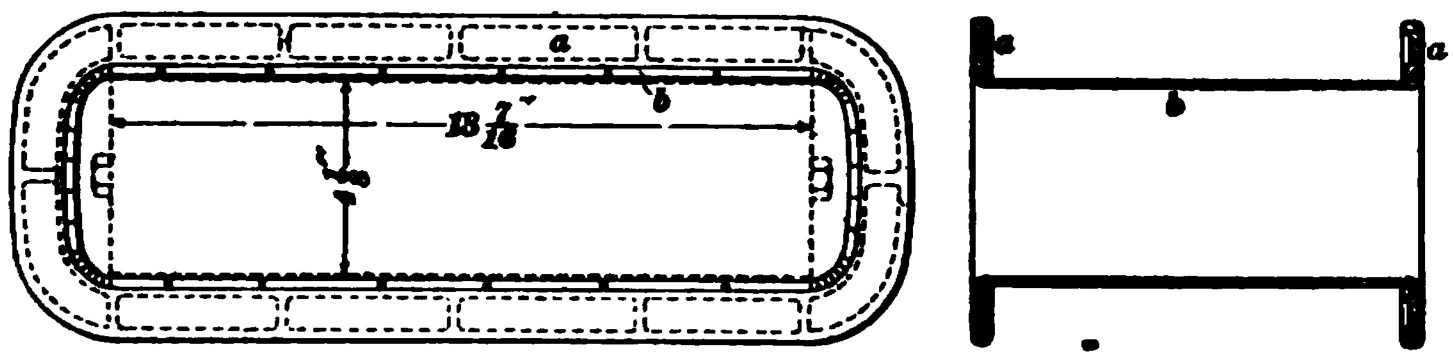


FIG. 19

current machines. These spools are made so as to slip over the pole pieces, and are usually held in place by pins projecting from the pole or by cap bolts screwed through lugs projecting from the end flanges of the spool. Fig. 19 shows an end elevation and a cross-sectional view of a spool of the style commonly used. The shell *b* is made of heavy sheet iron, and is flanged up at the ends, so that it may be riveted or soldered to the brass end flanges *a*, *a*. These flanges are usually recessed and provided with ribs to make them stiff and at the same time secure lightness. The ends of the spool are rounded out as shown, so as to give clearance for the heads of the bolts that clamp the pole pieces together. In designing field coils and spools, care must be taken to see that the depth of winding is not made such that the coils will interfere with each other when they are placed on the poles, and sufficient clearance must be provided, as at *a*, Fig. 20.

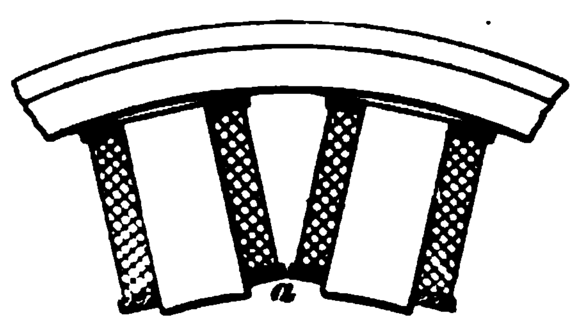


FIG. 20

39. Field coils are usually wound with double cotton-covered magnet wire, though in some large machines copper strip is used. The field spools of most modern revolving-field alternators are wound with flat copper strip bent on

FIG. 21

edge, as shown in Fig. 21, when (*a*) represents one of the laminated pole pieces, with its end insulations. A coil partly pulled apart is shown at (*b*). Insulation is placed between the layers of strip, and the outer edge of the strip

FIG. 22 FIG. 23

is left bare. A coil wound in this way is very solid and substantial, and the heat is readily radiated because the exposed strip conducts the heat to the air from the inner part of the coil. When field coils are provided with two

sets of windings (separately excited and series), the coils may be arranged on the spool, one on top of the other, as shown in Fig. 22, or side by side, as in Fig. 23. The construction shown in Fig. 23 is the better, because it admits of higher insulation and allows one coil to be repaired, in case of breakdown, without disturbing the other. On many modern machines the field coils are wound on forms and held in shape by taping so that it is not necessary to use spools.

INSULATION OF FIELD COILS

40. In many cases the fields are excited by coils that are provided with only one winding excited from a separate continuous-current machine. The exciter voltage in such cases is usually low, and it is unnecessary to take any unusual precautions in insulating the spools, as the maximum pressure tending to break down the insulation would not likely exceed 100 or 200 volts. Such spools may therefore be insulated in the same way as those for ordinary continuous-current machines.

41. Where the spools are provided with two windings, the series-winding is, in many cases, in direct connection with the armature, thus carrying the high potential to the field coils and subjecting the insulation to a large stress. Such windings must be thoroughly insulated, not only from one another, but also from the spools. Figs. 22 and 23 show the methods of insulating these coils. The shell is covered with several layers *a* of paper and mica interleaved, the insulation between the coils in Fig. 22 being also of the same material. The end insulations *b*, *b* and insulation *d* between the coils, Fig. 23, are made either of heavy collars of paper and mica, or of hardwood veneer treated with oil or other insulating material. Every precaution should be taken to make the insulation of these spools high, as they are liable to be subjected to just as high a voltage as the armature windings.

DESIGN OF FIELD

42. We will illustrate the method of obtaining the field dimensions by working out the design of a field suitable for the single-phase armature previously calculated. This field will be of the radial pole type shown in Fig. 12, the pole pieces being of wrought iron, as shown in Fig. 14.

BORE OF POLES AND LENGTH OF AIR GAP

43. Before proceeding with the design of the field, we must decide on the length of air gap to be used. It was shown, in connection with continuous-current machines, that for any given armature it was necessary to have a certain length of air gap; otherwise, the armature would react on the field so as to cause sparking when the machine was loaded. It has also been shown that the general effect of the armature reaction in an alternator is to weaken the field. If we wish an alternator to give good regulation, we can cut down the effect of the armature on the field by using a large air gap, and on this account it is quite common to find alternators provided with an air gap that is much larger than is necessary for mechanical clearance. A short gap would have the advantage of requiring only a small amount of magnetizing power on the field to set up a given flux; but, on the other hand, it would allow the armature to react strongly, the actual length of air gap used not being determined from considerations of the sparking limit, as it is in the case of direct-current machines. For belt-driven machines up to 250 or 300 kilowatts, $\frac{3}{8}$ inch to $\frac{1}{2}$ inch may be taken as fair values for the length of the double air gap. If the gap is made very large, of course a large amount of exciting power is required, so that it does not pay to increase the length of the gap much beyond the values given above. For large direct-connected machines, the gap necessary for mechanical clearance will usually be found sufficient to make the machine perform well electrically.

44. For the machine under consideration, we may, therefore, make the double air gap $\frac{3}{8}$ inch and the bore of the pole pieces $31\frac{3}{4} + \frac{3}{8} = 32\frac{1}{8}$ inches. The poles cover 50 per cent. of the armature, and the length of the arc will be

$$\frac{\pi \times \text{bore of poles} \times .5}{\text{number of poles}} \qquad \textbf{(10)}$$

or $$\text{arc} = \frac{\pi \times 32.125 \times .5}{12} = 4.2 \text{ inches}$$

The distance between the sides of the pole will be about $4\frac{1}{8}$ inches, as shown in Fig. 24. The length of the pole piece parallel to the shaft will be the same as the length of the armature core, $13\frac{7}{16}$ inches.

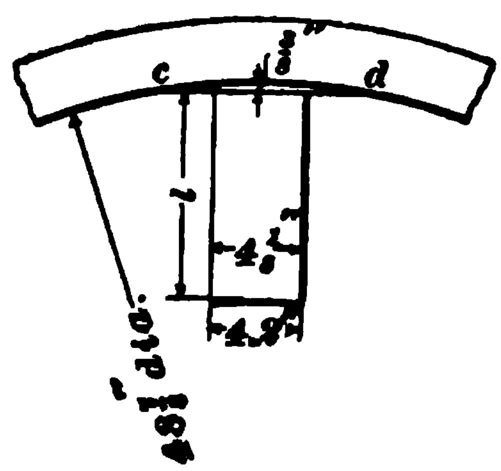


FIG. 24

45. All dimensions of the pole pieces are now known except their radial depth l, Fig. 24. The pole piece must be made long enough to accommodate the winding without making it too deep. Short pole pieces result in a yoke of small diameter and a correspondingly light machine. On the other hand, the spool winding must usually be deep when short spools are used. The depth of winding may not only be limited by the space between the poles, but deep windings are objectionable on account of their liability to overheat and the larger amount of copper required for them. If, however, the cores are made longer than is necessary, the winding is made unnecessarily shallow and the yoke of large diameter, thus making the machine heavy and the magnetic circuit long. In machines of the type under consideration, the length of the pole piece is usually from $1\frac{3}{4}$ to $2\frac{1}{2}$ times as long as it is wide. For a trial value, we will therefore take 8 inches as the length l. This can later be increased or decreased slightly to suit the windings, if found necessary. We will also allow $\frac{3}{8}$ inch, as shown in Fig. 24, for

the thickness of the flat part on the inside of the yoke against which the coils rest. This will make the inside diameter of the yoke $32\frac{1}{8} + 16 + \frac{3}{4} = 48\frac{7}{8}$ inches.

MAGNETIC FLUX THROUGH POLE PIECES AND YOKE

46. The **magnetic flux** that passes through the armature from one pole piece is Φ. A certain number of the lines leak across from one pole piece to the other without passing through the armature; hence, in order to get Φ lines in the armature, we must have Φ' lines in the pole piece, where Φ' is equal to Φ multiplied by the coefficient of leakage. The coefficient of leakage is generally somewhat greater for alternators than for direct-current machines, because the poles are usually fairly close together and expose quite a large surface from which leakage may take place. The larger the air gap compared with the leakage path between the poles, the greater will be the amount of leakage, since the lines always flow by the path offering the least resistance. The coefficient of leakage also varies with the size of the machine, being smaller for large machines than for small ones, and may have values ranging from 2 to 1.3 or less in very large machines. We will take the coefficient of leakage for the machine under consideration as 1.4.

47. The useful flux Φ from one pole is in the present case 2,235,000 lines. The flux through each pole piece will therefore be $\Phi' = 2{,}235{,}000 \times 1.4 = 3{,}129{,}000$.

The magnetic density in the field cores will be

$$\mathbf{B}_f = \frac{\text{flux through core}}{\text{cross-section}} \qquad (11)$$

$$= \frac{3{,}129{,}000}{4\frac{1}{8} \times 13\frac{7}{16}} = 56{,}400 \text{ lines per square inch}$$

It will be noticed that this density is well below that point at which wrought iron begins to saturate, so that

the sectional area of the pole pieces as determined by the polar arc is ample for carrying the magnetic flux.

48. The magnetic flux through the yoke is one-half that through the pole piece, because the lines divide, one half flowing in one direction and the other half in the other direction. The number of lines flowing through the cross-section of the yoke is, therefore,

$$\frac{\Phi'}{2} = \frac{3,129,000}{2} = 1,564,500$$

and the required cross-section of the yoke will be

$$A = \frac{\text{flux through yoke}}{\text{allowable density in yoke}} = \frac{\frac{1}{2}\,\Phi'}{\mathbf{B}_y} \qquad \textbf{(12)}$$

where $\mathbf{B}_y$ is the magnetic density at which the yoke is worked. The yoke density is usually low, as already explained, the yoke being made of cast iron. We will take 30,000 lines per square inch as the allowable value of $\mathbf{B}_y$, thus giving for the required cross-section

$$A = \frac{1,564,500}{30,000} = 52.1 \text{ square inches, nearly}$$

We will make the yoke 17 inches wide, so as to allow it to project over the pole pieces at each end. If we made the yoke rectangular in section, as shown by the dotted outline, Fig. 25, the thickness would be about $3\frac{1}{16}$ inches to give the requisite cross-section. Instead of using the rectangular shape, we will increase the thickness at the center to 4 inches and round off the yoke as shown, so as to keep the area about the same. This will give a heavier-looking yoke, and one that will present a better appearance generally than that with a rectangular section.

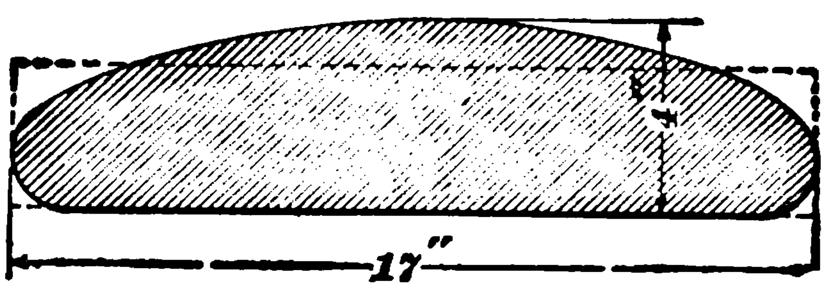


FIG. 25

CALCULATION OF FIELD AMPERE-TURNS

49. Since the dimensions of the field frame, armature, and air gap are now known, and the magnetic densities in these different parts are also known, the ampere-turns required to set up the magnetic flux can be calculated. In order to do this, it is best to consider one of the simple magnetic circuits shown by the dotted line *a–b–c–d–e–f*,

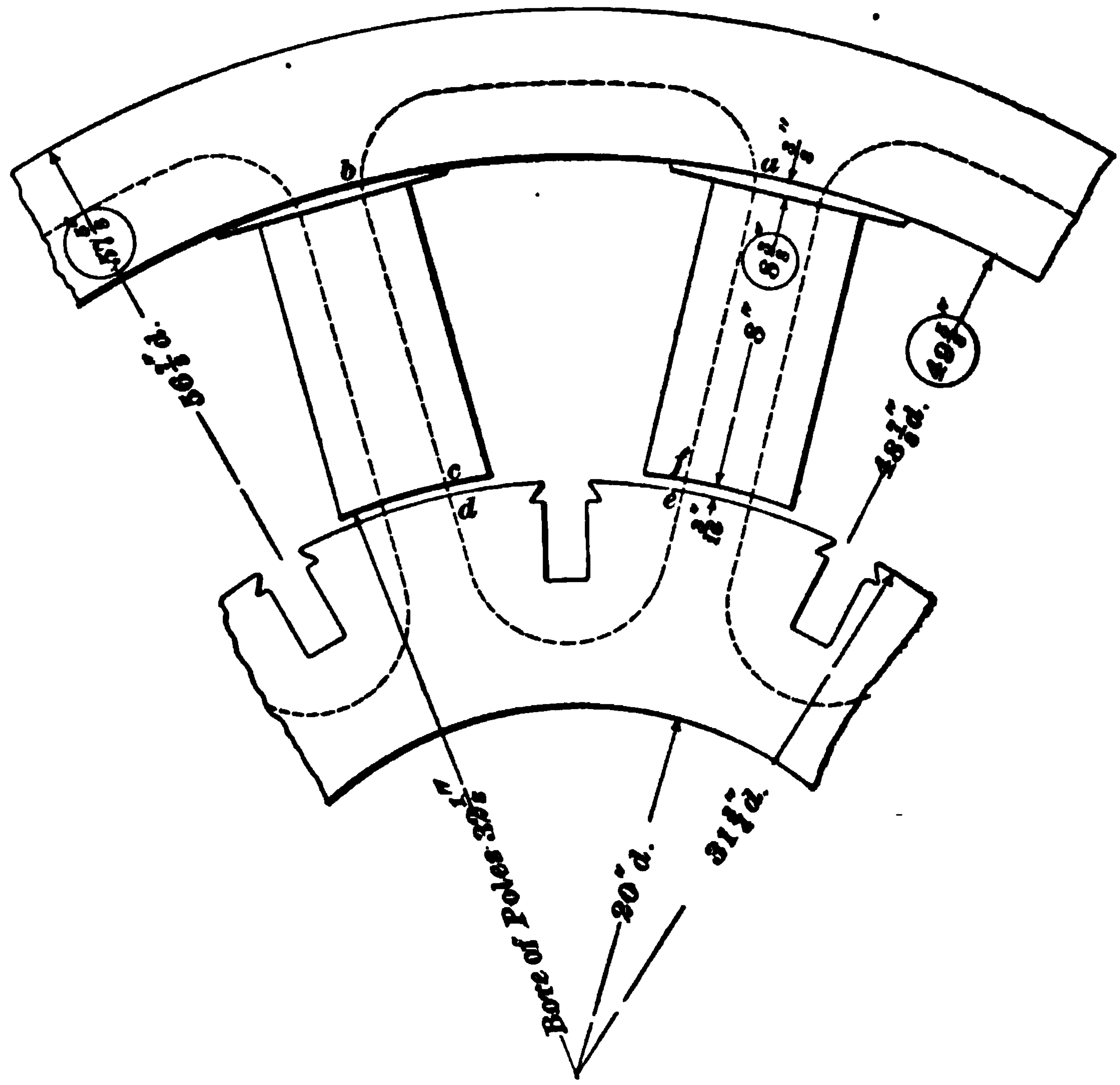


FIG. 26

Fig. 26. This path is made up of a portion of the yoke, two pole pieces, the double air gap, and the portion of the armature core shown. The dotted line represents the length of the average path through which the lines flow, and the ampere-turns supplied by the separately excited

coils on the two poles must be sufficient to set up the magnetic flux around this path. We may, for convenience in making calculations, split up the ampere-turns required for the whole circuit into the following parts:

1. Ampere-turns required for the double air gap $cd + ef$.
2. Ampere-turns required for the circuit through the two pole pieces $bc + af$.
3. Ampere-turns required for the path through the yoke ab.
4. Ampere-turns required for the path through the armature de.

50. The effective area of cross-section of the air gap through which the lines Φ flow will be taken as about equal to the area of the pole face. The lines will fringe to some extent at the edges of the pole, thus actually increasing the effective area slightly. The area is, however, cut down somewhat by the air ducts in the core, so that this will tend to counterbalance any increase in area due to fringing. We will therefore assume that the density is as taken at the outset, namely, 40,000 lines per square inch. The permeability of air is 1, and the total length of air gap is $\frac{3}{8}$ inch; hence, ampere-turns required for double air gap $= \mathbf{H} \times l \times .313 = 40{,}000 \times .375 \times .313 = 4{,}700$, nearly.

51. The magnetic density in the pole pieces has already been determined and found to be 56,400 lines per square inch. The length of path through the two pole pieces is $2 \times 8 = 16$ inches. By referring to the magnetization curves, *Dynamos and Dynamo Design*, Part 2, we find that it requires about 11 ampere-turns per inch of length to set up a density of 56,400 lines per square inch through wrought iron. Hence, ampere-turns required for field cores $= 11 \times 16 = 176$.

52. The yoke has been made of such cross-section that the density in it is 30,000 lines per square inch. The length of the path ab through the yoke can be scaled from the

drawing, and in this case is about $14\frac{1}{2}$ inches. For a density of 30,000 lines per square inch, the ampere-turns required per inch of length for cast iron are about 50. Hence, ampere-turns required for yoke $= 50 \times 14\frac{1}{2} = 725$.

53. The armature has been made of such cross-section that the density in the core is about 30,000 lines per square inch. The length of the path through the core can be obtained from the drawing; in this case it is about 12 inches. The ampere-turns required per inch of length for wrought iron at this density will be about 8. Hence, ampere-turns required for armature core $= 8 \times 12 = 96$.

54. The total ampere-turns that must be supplied by one pair of the separately excited field coils will be the sum of the ampere-turns required for the different parts of the magnetic circuit; hence, total ampere-turns $= 4,700 + 176 + 725 + 96 = 5,697$, say 5,700.

The student will note that because the magnetic densities in the iron parts of the circuit are low, and also because the lengths of the different paths are short, the ampere-turns required for the iron part of the circuit are small compared with those required for the air gap, which has a high magnetic reluctance. The ampere-turns required for the armature core might in many cases be neglected without serious error. It follows from this that if it is found necessary later to lengthen or shorten the pole pieces slightly, in order to accommodate the winding, the corresponding resulting change in the ampere-turns will not be appreciable.

CALCULATION OF SEPARATELY EXCITED WINDING

55. Having determined the ampere-turns to be supplied by each pair of separately excited coils, the next step is to design a winding for these coils that will supply the required number of ampere-turns. The size of wire can readily be determined when the mean length of a turn and

the voltage across the coils are known. In order to get at a value for the mean length of a turn, we must adopt a trial value for the depth of the winding. Suppose we make the spool flanges $1\frac{1}{4}$ inches deep, as this will give a spool of dimensions well suited to the field shown in Fig. 26, allowing plenty of clearance space between the coils when they are slipped over the poles. The clearance between the shell and field core will be, say, $\frac{3}{32}$ inch all around, and we will allow $\frac{5}{32}$ inch on each side for the thickness of the shell and insulation. The series and separately excited coils will be arranged side by side, as shown in Fig. 23. We will have a clear depth of winding of 1 inch, allowing for clearance and insulation as above. The shape of the spool will be as shown in Fig. 19, and the mean length of a turn can readily be measured off the drawing. In this case the mean length of a turn will be about 41 inches, or $3\frac{5}{12}$ feet.

56. The separately excited coils are connected in series, so that the voltage across any pair of coils will be the voltage across all the coils divided by the number of pairs of poles on the machine. The voltage applied to the separately excited field is equal to the voltage generated by the exciter less whatever drop there may be in the regulating rheostat. Let E represent the E. M. F. generated by the exciter, and e the drop in the rheostat. The pressure applied to one pair of coils will then be

$$\frac{E - e}{\frac{p}{2}}$$

where p = number of poles;

or
$$\frac{2(E - e)}{p}$$

The current in the field will be

$$i = \frac{\text{E. M. F.}}{\text{resistance}} = \frac{\frac{2(E - e)}{p}}{R} \qquad (13)$$

where R is the resistance of a pair of spools.

But the hot resistance R of a pair of spools may be expressed as follows:

$$R = \frac{l_m \times T}{m} \qquad (14)$$

where l_m = mean length of a turn in inches;
T = number of turns on a pair of spools;
m = circular mils cross-section of field wire.

Substituting in formula **13** the value of R as given by formula **14**, we get

$$i = \frac{2\,(E - e)\,m}{p \times l_m \times T} \qquad (15)$$

and

$$m = \frac{p \times l_m \times T \times i}{2\,(E - e)}$$

$$= \frac{p \times l_m \times i\,T}{2\,(E - e)} \qquad (16)$$

The values of the quantities T and i are not known separately, but their product is known, since it is the ampere-turns supplied by one pair of spools. Hence, we may write

$$\text{circular mils cross-section of separately excited field wire}$$
$$= \frac{\text{number of poles} \times \text{mean length of a turn in inches} \times \text{ampere-turns}}{2\,(\text{voltage of exciter} - \text{drop in field rheostat})}$$

Or, the cross-section in circular mils of the wire necessary for the separately excited winding of an alternator is found by taking the product of the number of poles, the mean length of a turn in inches, and the ampere-turns supplied by one pair of spools, and dividing by twice the voltage of the exciter less the drop through the field rheostat.

The size of wire could be worked out equally well by considering the ampere-turns supplied by all the coils instead of a single pair, and taking the total voltage instead of the voltage across a pair of spools. It is best, however, to make the calculations with reference to a pair of spools in order to avoid confusion, because the ampere-turns were calculated for a pair of spools.

57. The exciter voltage E is commonly 110 volts, though other voltages are sometimes used with large machines. The use of 110 volts is common, because it permits the use of an ordinary 110-volt incandescent dynamo as an exciter. We will assume that the field for which we are making calculations is supplied from a 110-volt exciter, and that the normal drop in the rheostat is 10 volts. This will make the pressure across the twelve field coils 100 volts total. We then have

$$\text{circular mils} = \frac{12 \times 41 \times 5,700}{200} = 14,022$$

The nearest size to this is No. 9 B. & S. having a cross-section of 13,090 circular mils. We will therefore adopt this size of wire for the separately excited field, the slight difference in cross-section being compensated for by cutting out a little of the rheostat resistance.

58. The current density in the field should be considerably lower than in the armature, because the field windings are deeper and the heat is not so easily dissipated. The current in the separately excited winding is about the same, no matter what load the alternator is carrying, and in this respect is not like the current in the series-coils, which varies with the load. For these reasons, it is not safe to allow much less than 1,000 or 1,200 circular mils per ampere in the separately excited winding, and in cases where the winding is very deep a larger allowance than this may be required. In the present case we will take 1,100 circular mils per ampere as a fair value, thus limiting the current to $\frac{13090}{1100}$ = 11.9 amperes.

59. With a field current of 11.9 amperes, the number of turns required per pair of spools will be $\frac{5,700}{11.9} = 478$ turns, nearly. Each coil should then have 239 turns of No. 9 B. & S. double cotton-covered wire. The diameter of this wire over the insulation will be about 126 mils, and if the coil is wound in eight layers, the depth of winding will be

1.008 inches, so that an eight-layer winding will fit the 1-inch winding space on the spool. If we use thirty turns to a layer, we will have 240 turns per spool. This is an increase of one turn over the number actually required, but it will be better to use this winding than to have an uncompleted layer, since the difference is so small. The length of winding space occupied by the coil will be $30 \times .126 = 3.78$ inches, or, say, $3\frac{7}{8}$ inches, so as to be sure of enough room.

S

FIG. 27

The separately excited coil will therefore be wound with eight layers of No. 9 wire with thirty turns per layer, the winding space occupied being $3\frac{7}{8}$ inches long and 1 inch deep. The use of 240 turns per spool, instead of 239 turns, will not affect the current appreciably. The upper coil *S*, Fig. 27, shows the arrangement of this coil on the spool.

COMPOUND, OR SERIES-FIELD, WINDING

60. The **compound winding** must provide a sufficient number of ampere-turns to compensate for the falling off in voltage at the terminals due to the resistance of the armature and the combined effects of armature inductance and armature reaction. The compound winding must also provide the ampere-turns necessary for any increase in terminal voltage in cases where the machine is to be overcompounded. The calculation of the compound winding depends to a large extent on data obtained from machines of a similar type. Its determination for a machine of new type is always more or less experimental.

61. The current that is led through the series-winding is first rectified, as explained in former articles, and as the current increases in proportion to the load, the field is strengthened proportionally, provided the magnetic circuit is not saturated. This is usually the case with alternators, so that we may assume that any change in the field current is accompanied by a corresponding change in the field strength. It is not usual to send the whole of the current around the series-fields; part of it is shunted through a German-silver resistance, by varying which the amount of compounding can be varied. This allows a considerable adjustment of the series-coils, so that their effect on the performance of the machine can be varied through a wide range without changing the series-winding in any way. Sometimes the whole current is not rectified, a portion of it being shunted around by means of a resistance connected to the two sides of the rectifier. In this case the shunt must revolve with the armature, and is usually mounted on the armature spider. Revolving shunts are generally used on machines of any considerable size, as they avoid the difficulty of commutating a large current. Compound coils are only necessary on the fields of machines that have high armature inductance or resistance, or on machines that must give a considerable rise in voltage from no load to full load. Other types of machines can be made to give sufficiently good regulation by the use of separately excited coils only. Most of the alternators of large output installed in modern power plants are plain separately excited machines.

62. The drop due to the resistance of the armature is easily calculated when the armature resistance is known, as it is equal to the product of the armature resistance and the full-load current. In this case, therefore, the armature drop will be $45.4 \times .7 = 31.78$ volts.

63. The machine is to supply 2,000 volts at no load and 2,200 volts at full load; the compound winding must therefore strengthen up the field sufficiently to generate this

200 additional volts, as well as the 31.78 volts required to overcome the resistance of the armature. If there were no armature inductance or armature reaction, the total volts that would be generated at full load would be about 2,232. The ampere-turns supplied by two separately excited coils (i. e., 5,700) are sufficient to generate 2,000 volts; hence, if the above conditions were attained, the ampere-turns on the field at full load would have to be $\frac{2232}{2000} \times 5{,}700 = 6{,}361$, and the ampere-turns that would be supplied by the series-coils would be $6{,}361 - 5{,}700 = 661$, or about 331 on each spool. For a machine of this kind, however, this would represent only a very small part of the series ampere-turns that would actually be required, because, in the first place, the field is weakened by the reaction of the armature, and, secondly, a large E. M. F. has to be generated to force the current through the armature against its inductance. In machines of this type the compound ampere-turns may be as much as two-thirds or more of the ampere-turns supplied by the separately excited coils. In the present case, therefore, we will design each spool so that it will be capable of supplying about 2,500 ampere-turns. If this should prove to be somewhat more than is actually required, it can easily be cut down by allowing more current to flow through the shunt.

64. We will assume that 70 per cent. of the current at full load flows through the series-coils, the remaining 30 per cent. flowing through either the revolving or stationary shunts. This will make the current in the series-coils $45.4 \times .70 = 31.78$, say 32 amperes, nearly. The number of turns required for each series-coil will then be $\frac{2500}{32} = 78.4$ turns.

65. The current density in the series-coils should be about the same as that in the separately excited windings. If we allow 1,100 circular mils per ampere, as before, we get a cross-section of $32 \times 1{,}100 = 35{,}200$ circular mils. Two No. 8 wires in parallel give 33,020, while two No. 7

wires give 41,640. We will adopt the conductor made up of two No. 8 wires, because the current in the series-coils is not apt to be continuously at 32 amperes, and we can therefore afford to use a cross-section that is a little on the small side. The outside diameter of No. 8 wire with cotton insulation is about .140 inch; hence, in a winding space 1 inch deep we can place seven layers. If we use 11 turns per layer, we will have 77 turns per coil, and can compensate for the slight decrease in the calculated number of turns (78.4) by changing the shunt a little, so as to cause a correspondingly larger amount of current to flow through the coils. Each turn consisting of two wires in parallel will occupy a length along the winding space of .280 inch, and 11 turns will take up a space of $.280 \times 11 = 3.080$ inches, say $3\frac{1}{8}$ inches. We will allow $\frac{3}{16}$ inch at each end and between the coils for the hard-wood insulating collars, thus making the total axial length taken up by the windings and insulation $3\frac{7}{8} + 3\frac{1}{8} + \frac{9}{16} = 7\frac{9}{16}$ inches. The brass flanges on the spools will be about $\frac{1}{4}$ inch thick, so that the total space taken up on the pole piece will be $7\frac{9}{16} + \frac{1}{2} = 8\frac{1}{16}$ inches. The radial length of the pole piece as originally assumed was 8 inches; it will therefore be necessary to lengthen out the poles a little, in order to accommodate the spool, and increase the diameter of the yoke correspondingly. It is best to have the pole project beyond the spool flange a little, as it keeps the flanges away from the armature and makes it easier to fasten the spools in place. We will therefore make each pole piece $8\frac{3}{8}$ inches long instead of 8 inches. Fig. 27 shows a section of the spool with both windings in place. The pole piece is indicated by the dotted outline. This change in the length of the pole piece will make the inside diameter of the yoke $49\frac{5}{8}$ inches, and the outside diameter $57\frac{5}{8}$ inches, as shown in Fig. 26, where the final dimensions are encircled by rings. The spools are held in place on the poles by pins (not shown in the figure), which are fixed in the pole pieces so as to prevent the coils slipping down on to the armature.

LOSS IN FIELD COILS

66. The **loss in the field coils** should be determined, in order to see if sufficient radiating surface is provided to dissipate the heat. The resistance of the twelve separately excited coils will be

$$R_s = \frac{12 \times 240 \times 41}{13{,}090} = 9 \text{ ohms, approximately}$$

since there are 240 turns on each spool.

The $i^2 R$ loss in the separately excited coils will therefore be $(11.9)^2 \times 9 = 1{,}274$ watts.

67. The resistance of the twelve series-coils is

$$R_c = \frac{12 \times 77 \times 41}{33{,}020} = 1.15 \text{ ohms}$$

The $I^2 R$ loss in the series-coils will therefore be $(32)^2 \times 1.15 = 1{,}178$ watts, nearly.

68. The total loss in the field will be 2,452 watts, or about 2.4 per cent. of the output. This is the maximum loss when the machine is working at its full output. The average field loss would probably not be over 2 per cent. of the output, as the loss in the series-coils would not be as high as 1,178 watts all the time. The loss per coil will be $\frac{2452}{12} = 204$ watts. The surface of each coil (not counting the ends) is about 350 square inches. This area is obtained by multiplying the perimeter of the coil as obtained from the drawing by the length of the coil along the pole piece. This area gives an allowance of 1.7 square inches of surface per watt, which is sufficient to insure a rise in temperature not exceeding 40° C. As far as heating goes, the design of the winding is therefore satisfactory.

69. The curve shown in Fig. 28 gives the relation between the average field $I^2 R$ loss and the output for

alternators of good design. For a 100-kilowatt machine the

Relation between field I^2R loss and output of alternator.

FIG. 28

average loss is about 1.7 per cent., which is slightly lower than that for the machine just calculated.

MECHANICAL CONSTRUCTION

FIELD FRAME AND BED

70. Fig. 29 shows the **field frame,** with bed and bearings, for the machine designed, and will serve to illustrate the general method of construction used for machines of this type. In this case, the field is shown as a separate casting bolted to the base, but, as mentioned before, many machines are constructed with the lower half of the field cast with the base. Where the machine is of large size, it becomes difficult to cast the field and bed together, and the construction shown is usually adopted in such cases. The field is usually set down into the bed, as this lowers the center of gravity and tends to make the

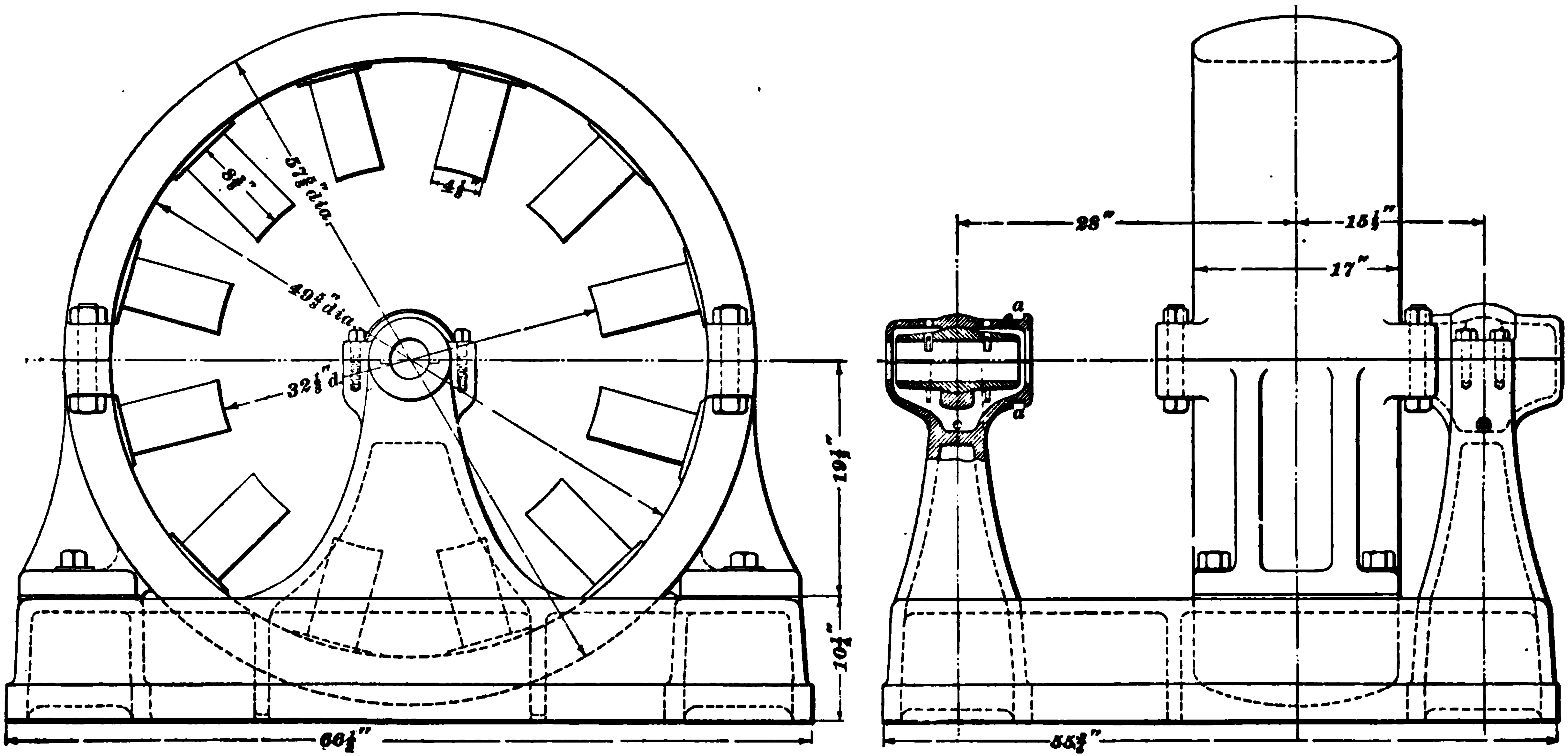


Fig 29

machine run steadier. The distance between the centers of bearings is determined by the over-all length of the armature and the space taken up by the collector rings. The bed itself is almost exactly similar to the beds used for multipolar continuous-current machines; it is made hollow and provided with ribs to insure stiffness. The thickness of metal in the bed will vary from about $\frac{1}{2}$ inch or $\frac{5}{8}$ inch up to $1\frac{1}{4}$ inches or $1\frac{1}{2}$ inches for machines varying in size from about 50 to 500 kilowatts. Self-oiling bearings of the ring type are used almost exclusively. The bearing pedestals, as shown in Fig. 29, are cast with the base, though in many large machines it is common practice to cast them separately and bolt them to the bed. The bearing cap and pedestal is grooved at *a a* to receive the rocker-arm, which carries the rectifier brushes. Some makers place the rectifier and collector rings outside the bearing and bring the connecting wires through the shaft; in such cases the outside end of the bearing cap and pedestal must be grooved to receive the rocker-arm. Machines of the type shown are usually arranged so that they can be mounted on rails in the same manner as continuous-current machines.

COLLECTOR RINGS AND RECTIFIER

71. One of the distinguishing features of an alternator is the arrangement by which the current is collected. The commutator of the continuous-current machine, which is usually made up of a large number of parts, is replaced, in a simple alternator, by two or more plain collector rings. In case the alternator is compound-wound, the commutator is replaced by two or more **collector rings** in combination with a **rectifier.** Although there are, in general, a small number of parts connected with a collector as compared with a commutator, the mechanical construction of the collector must be carefully carried out, because it is often necessary, where revolving armatures are used, to secure high insulation. Fig. 30 shows a construction that may be

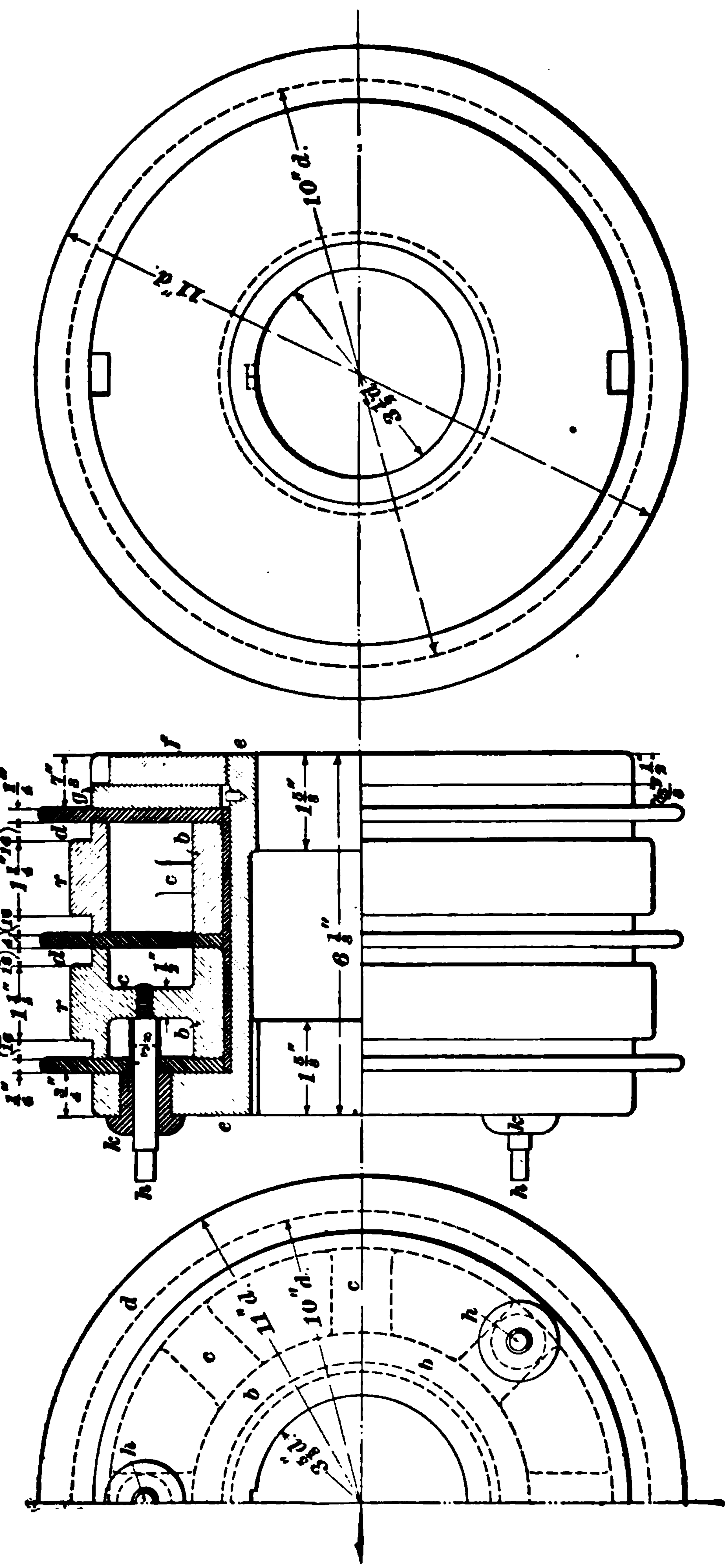


FIG. 30

used for simple collector rings. Such a pair of rings would be suitable for a single-phase alternator with a separately excited field winding only. The same construction could be used for separately excited two-phase or three-phase machines, the only difference being in the number of rings employed. The rings *r*, *r* are made of cast copper, which must be free from blowholes or imperfections tending to cause uneven wear. These rings are usually made heavier than is necessary for collecting and carrying the current, in order to make them strong mechanically and to allow for wear. Fig. 30 shows the construction used for rings that are subjected to a pressure of about 2,000 volts. The rings are cast with a hub *b*, which supports the rings by means of the spokes *c*. The insulation *d* between the disks is usually made of either red fiber or hard rubber, the latter being preferable, especially for high potentials. These insulating disks should be at least $\frac{1}{4}$ inch thick, in order to keep them from breaking easily, and they should also project some distance above the surface of the rings, in order to avoid any danger of the current arcing over from one ring to the other. The insulating washers and collector rings are assembled on a shell *e*, made either of cast iron or brass, the latter being preferable for collectors of small size. This shell is thoroughly insulated with several layers of mica, and the assembled collector is clamped firmly in place by means of the nut *f* and washer *g*. When the collector is of large diameter, it is usually clamped up by means of bolts instead of the nut *f* The connections to the rings are made by two copper studs *h*, which pass through the back of the shell and connect to each of the rings by being screwed into one of the spokes, as shown. These studs are heavily insulated throughout their length by tubes made of mica or hard rubber. After the terminals of the armature winding have been attached to the studs, all exposed parts should be heavily taped to avoid any danger of arcing from one terminal to the other. Where the studs pass through the back of the shell, they are insulated by thick hard-rubber bushings *k*.

72. The dimensions of the rings are determined quite as much by mechanical considerations as by the current that they are to collect. The surface of the rings should be wide enough to present sufficient collecting surface, and they should be thick enough to allow for a reasonable amount of wear. Such rings should collect at least 200 amperes per square inch of brush contact surface. This assumes that copper brushes are used, which is often the case with alternators. The freedom of carbon brushes from cutting and their better performance generally have resulted in their being used largely on alternators, though, of course, their advantages as regards the suppression of sparking do not have the force here that they do with direct-current machines. Carbon brushes require about three times as much contact surface, for a given current, as copper brushes, and this large collecting area is usually obtained by using a number of brushes distributed around the circumference of each ring, instead of increasing the width of the ring itself. The rings should not be made of too large diameter, or the rubbing velocity between the brush and ring will be high, thus tending to cause uneven wear and cutting. On the other hand, if the rings are made of very small diameter, they must be made wide to present sufficient collecting surface, thus necessitating the use of wide brushes. If a large collecting surface is required, it is best to use a ring of moderately large diameter, and use several brushes on each ring. From 1,500 to 2,500 feet per minute are fair values for the peripheral speed of collector rings for belt-driven machines. The rings shown in Figs. 30 and 31 are 10 inches in diameter.

On large revolving-field alternators, the collector rings are usually made of cast iron instead of copper. This is much cheaper, and it is found that carbon brushes bearing on cast-iron rings give excellent results, the iron ring taking on a good polish. On these large machines, the collector rings are usually made in halves, suitably fastened together, so that the rings may be put in place or removed without disturbing any of the heavy parts of the alternator.

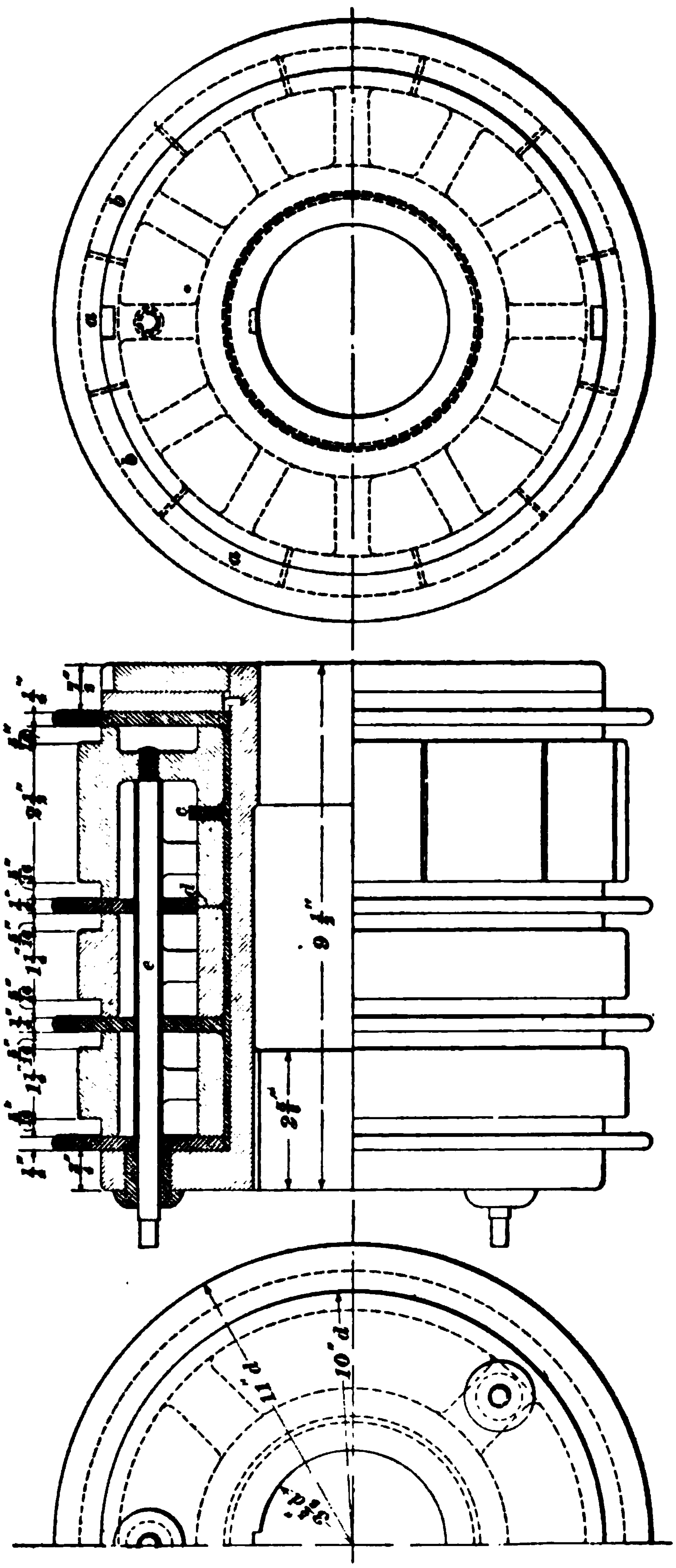


FIG. 31

73. For compound-wound machines, it is necessary to have a rectifier in addition to the collector rings. The rings and rectifier are usually built up together, though some makers mount them on the shaft separately. Fig. 31 shows a combined pair of collector rings and rectifier suitable for the single-phase machine designed. The rings are made 10 inches in diameter and 1¼ inches wide, the construction used being the same as that already described. The rectifier is made up of two castings, each having six sections, those belonging to one casting being marked *a*, and those belonging to the other, *b*. These two castings are separated by the mica collar *c*, while mica insulation is provided between the segments *a* and *b*, as in a regular continuous-current commutator. One set of segments connects to one of the collector rings through the hubs, as shown at *d*. The other rectifier casting is connected to the stud *e*, which is, in turn, connected to one terminal of the armature winding. The other stud is connected to the remaining collector ring. The details of construction will be understood by referring to the drawing, as they are almost identical with those described in connection with Fig. 30.

BRUSHES AND BRUSH HOLDERS

74. Copper **brushes** are generally used on the smaller sizes of alternators, and copper leaf or wire brushes similar to those used for direct-current machines are employed on many machines, though carbon brushes are now largely used on account of their superior wearing qualities. It is best to have at least two brushes for each col-

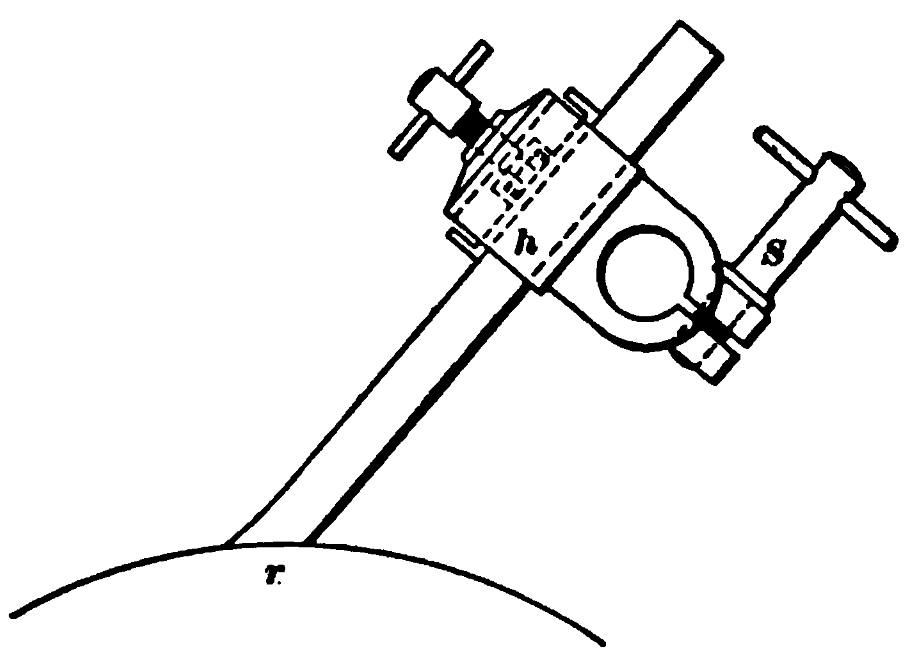


FIG. 32

lector ring, though this is hardly as essential as with

direct-current machines, because collector-ring brushes do not need as much attention while the machine is running as those used with commutators; for this reason, a large number of machines are built with only one brush for each collector ring. Two or more brushes should, however, be used for each terminal of the rectifier, because these brushes are liable to need more or less adjustment while the machine is running. The holders used should be so designed that the copper brush will press on the rings at an angle of about 45°. Any good form of copper brush holder used on continuous-current machines will answer equally well for an alternator. Such a holder should be arranged so that the brushes may be lifted from the commutator and held off, and the pressure of the brush on the ring should be easily varied. The pressure of the brush on the ring may be provided by making the brush itself act as a spring, or the holder may be provided with a spring, the tension of which is adjustable. Fig. 32 shows a simple type of holder that has been used considerably on alternators. The brush is made long enough between the holder *h* and the ring *r* to render it flexible and allow it to follow any unevenness of the surface. The pressure on the ring can be varied by changing the position of the holder on the stud by means of the clamp *S*. One advantage of this style of holder is that the current has no loose contact surfaces to pass through between the brush to the brush-holder stud. The carbon brush holders used on alternators are similar to those used on direct-current machines and require no special description.

BRUSH-HOLDER STUDS

75. Brush-holder studs follow the same general design as those used for continuous-current machines, special care being taken to have them very well insulated. Fig. 33 shows a common type of stud and the method used for insulating it. The brass stud *a* is circular in cross-section and is provided with a shoulder *g* that clamps against a

washer *h*. The stud is insulated from the rocker-arm by a heavy hard-rubber bushing *l* and washers *b*. The bushing *l* is let into the washers *b*, as shown, in order to break up the path by which the current tends to

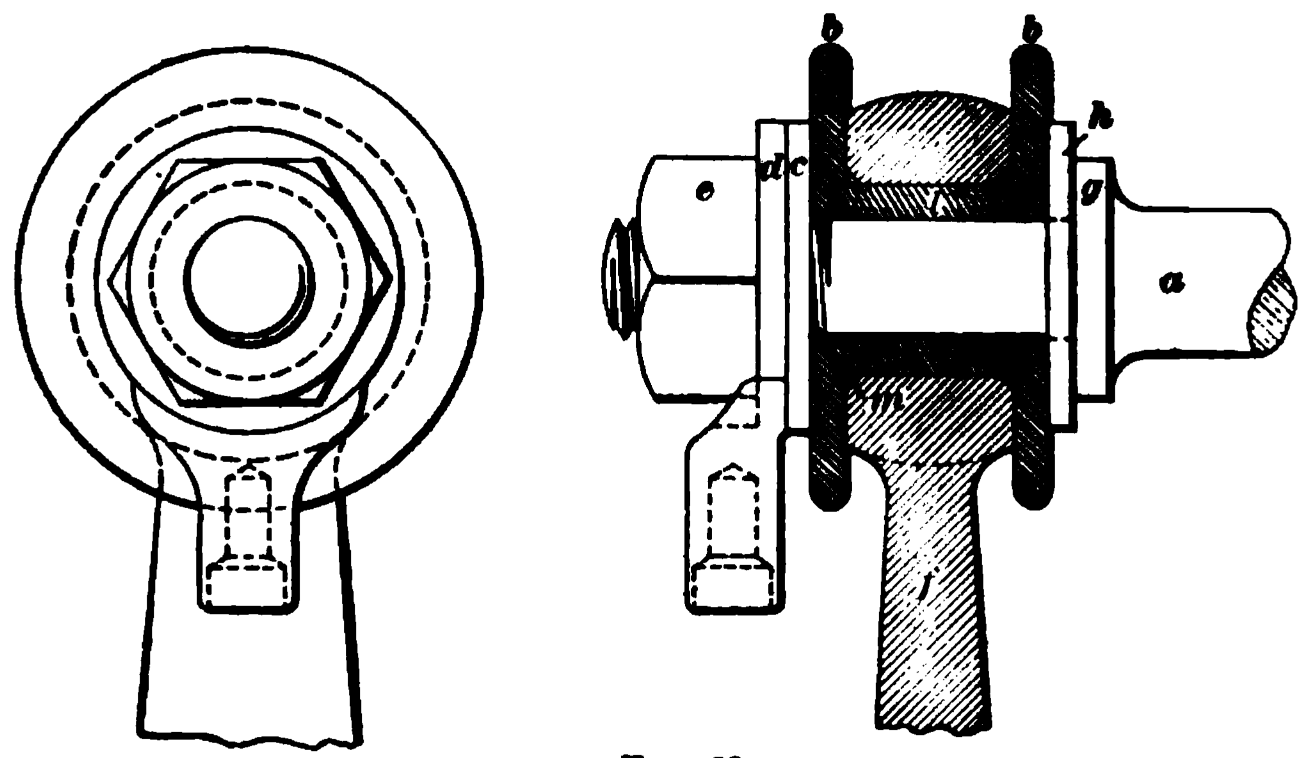


FIG. 33

jump from the stud to the supporting casting. The sharp corners of the casting should also be removed, as shown at *m*. The cable terminal *d* is clamped between the washer *c* and the nut *e*. Fig. 34 shows another method that is sometimes used for mounting and insulating brush-holder studs. A hard-rubber tube *a* fits tightly over the

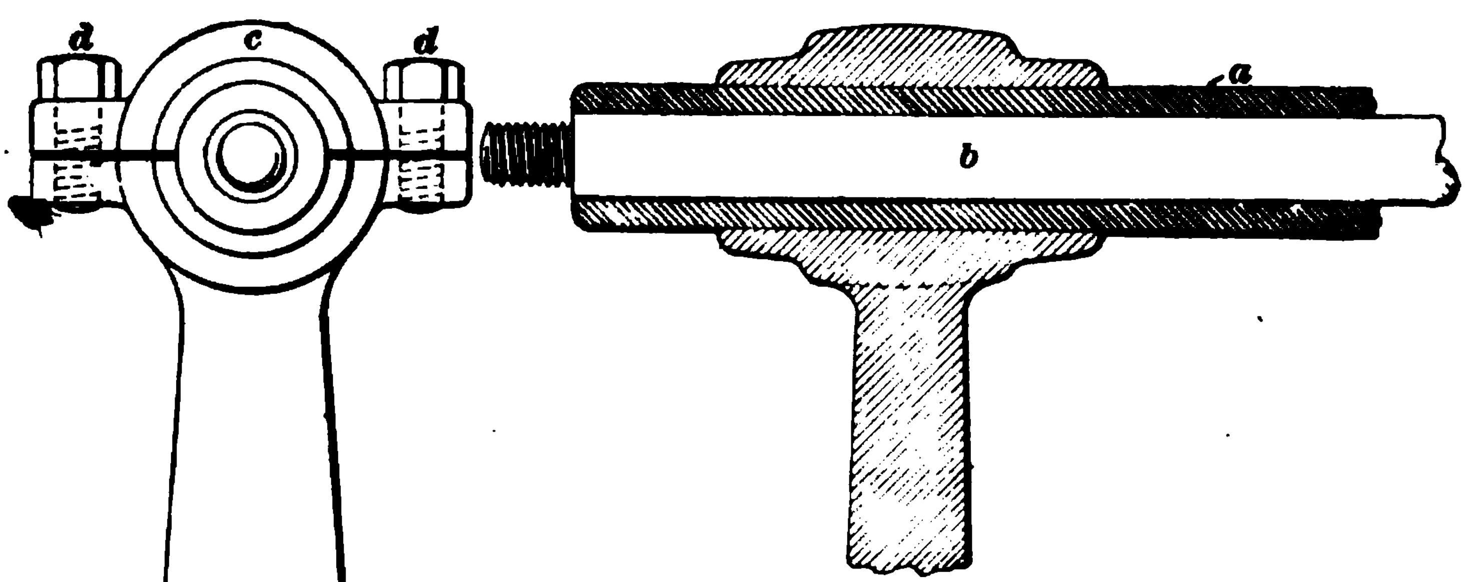


FIG. 34

stud *b* and completely covers it except at the points where the brush holders and cable connections are placed. The brush-holder stud is clamped to the rocker-arm, as shown, by means of the cap *c* and the cap bolts *d*. Connection is

made to the cable at the end of the stud. This construction gives very good insulation between the stud and the rocker, because the insulation is unbroken and no path is open for the current to jump across unless it punctures the tube itself.

76. The studs that carry the rectifier brush holders should be mounted on a rocker-arm, so that they may be adjusted, with reference to the field, in the same manner as the brushes of a direct-current machine. The studs for the collector-ring brushes may be carried on the same rocker-arm, or may be mounted on a stationary stand bolted to the bed of the machine.

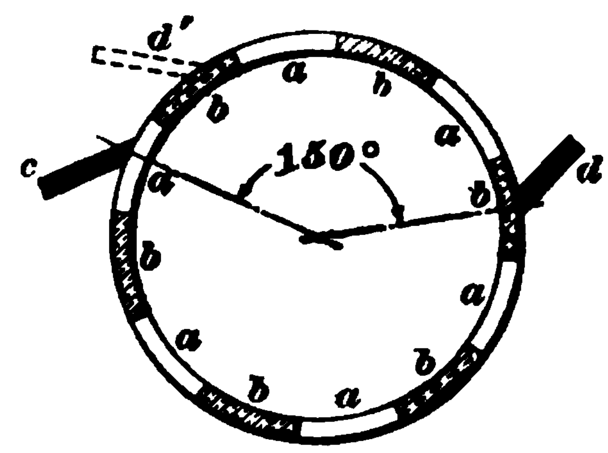


FIG. 35

The collector-ring brushes do not need to occupy any definite position relative to the field; hence, it is not necessary that they should be mounted on the rocker-arm, though this is very often done for the sake of convenience and cheapness of construction. The angular distance between the arms of the rocker carrying the rectifier studs will depend on the number of poles on the machine. Suppose Fig. 35 represents the rectifier for the twelve-pole machine worked out. All the light sections belong to one casting and the dark ones to the other. The angular distance from center to center of segments is 30°. When one set of brushes is on a light segment, the other set must be on a dark segment; hence, the brushes might occupy the position *c d'*. This, however, would bring the brushes too close together, and we will place the rocker-arms so as to make them as far apart as possible, and still have them conveniently located. We will therefore place the rocker-arms carrying these brush-holder studs 150° apart, thus bringing the brushes into the position *c d*.

77. Fig. 36 shows a rocker-arm suitable for the single-phase machine designed. The arms *a*, *b* are 150° apart, and

carry the rectifier studs, the arms *c*, *d* for the collector-ring studs being carried on the same rocker. The hub *e* is bored to fit the groove in the bearing cap, and the rocker is made in halves, as shown, so as to be easily removable, and held

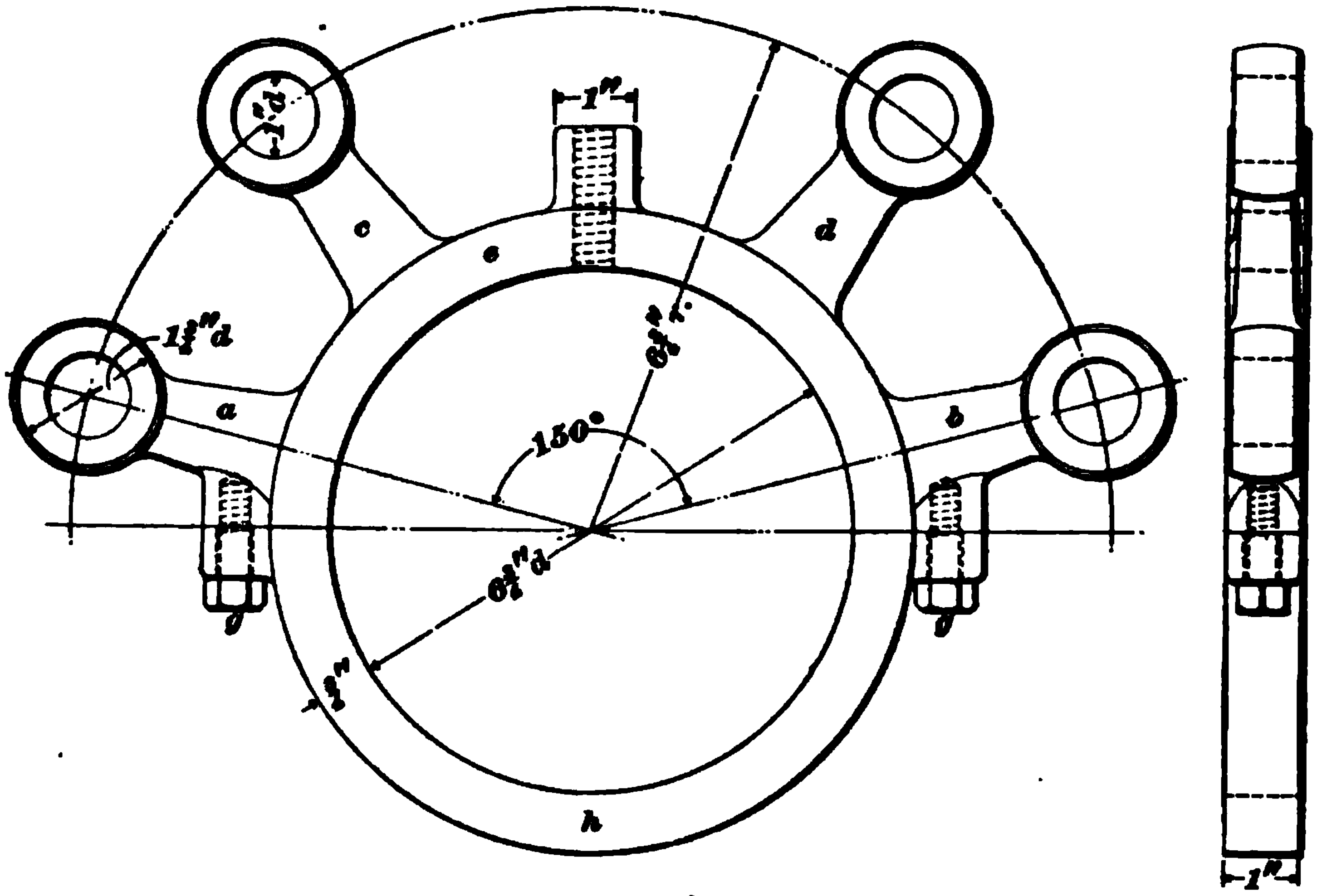


FIG. 36

together by bolts *g*, *g*. The lug *f* is tapped out to receive a handle, which serves both to shift the rocker and clamp it in any desired position by screwing it down against the seat on which the rocker moves.

SHAFTS

78. Shafts for alternators are designed according to the same rules as those for direct-current machines. These shafts are usually made larger than the size called for by the power to be transmitted. Stiffness is an essential feature of all armature shafts, and in order to secure this, they are made quite large, considering the actual amount of power that they must transmit. This is necessary, because the shaft must not only support the weight of the armature, but it may also be called on to stand heavy magnetic pulls if the field is not evenly balanced. A shaft suitable for the

100-kilowatt machine is shown in Fig. 37. This is designed for a pulley journal, 13 in. × 4 in., and a collector end journal, 10 in. × 3¼ in. The keyway *a* is for the armature spider key. The central portion of the shaft where the spider fits on is usually made a little large, so that the spider may be forced into place. The keyway for the pulley is shown at *b*. All internal corners of the shaft should be

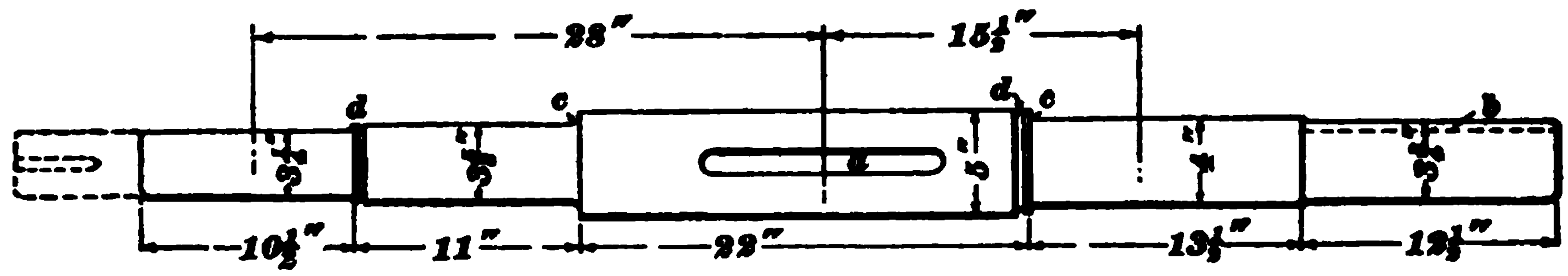


Fig. 37

rounded, as shown at *c*, *c*, and oil grooves *d*, *d* should be provided to prevent the oil from working its way out of the boxes by creeping along the shaft. In many cases the exciter is driven from a pulley mounted on an extension of the armature shaft. The shaft must then be furnished with a keyway on the extension for the exciter pulley, as shown by the dotted lines.

PULLEYS

79. Ordinary cast-iron **pulleys** are usually employed. Broad-faced pulleys are usually provided with two sets of arms, and the pulleys, on the whole, are constructed somewhat heavier than those used for general transmission work. Large pulleys should be made in halves, and strongly bolted together both at the hub and rim. The diameter of the pulley is determined by the linear speed at which it is allowable to run the belt. A fair average value for this belt speed may be taken from 4,000 to 5,000 feet per minute for machines varying in size from 50 to 500 kilowatts. It is not advisable to run the belt at a speed much higher than 5,500 feet per minute, as the grip between the belt and pulley becomes less with higher speeds. The diameter of the pulley in inches is then given by the expression

$$\text{diameter of pulley} = \frac{12\,S'}{\pi \times \text{R. P. M.}} \qquad \textbf{(17)}$$

where S' = belt speed in feet per minute.

Applying this to the 100-kilowatt machine, and taking 4,500 feet per minute as a fair value for the belt speed, we get

$$\text{diameter of pulley} = \frac{12 \times 4{,}500}{3.14 \times 600} = 28.6 \text{ inches}$$

We will make the diameter of the pulley 28½ inches, as shown in Fig. 38. The face of the pulley must be slightly wider than the belt necessary to transmit the given amount of power at the required belt speed. The belt must be of

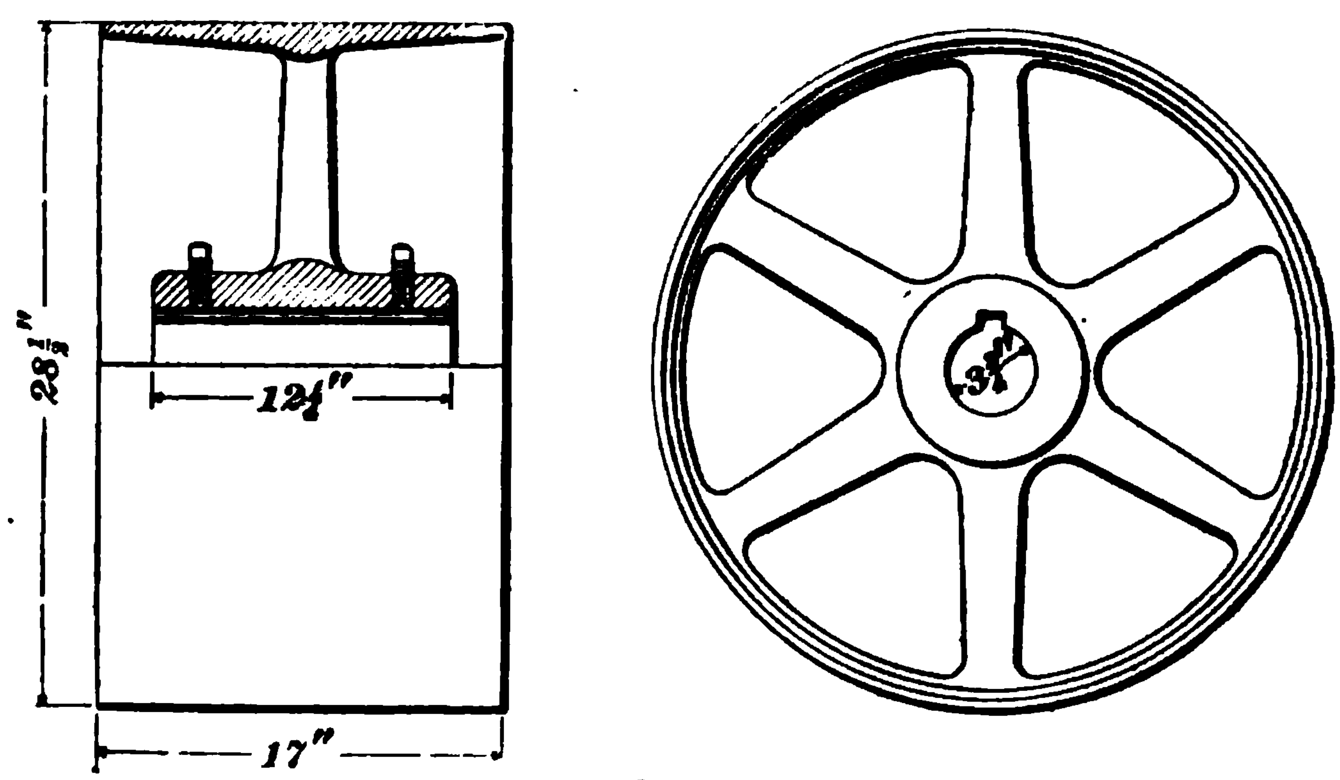


FIG. 38

such width that the strain on it per unit width will not be more than the belt can safely carry. The amount of power that can be transmitted per unit width of belt depends on the quality and thickness of the belt as well as on the belt speed. Assuming that a double thick belt is used, we may determine the width of belt necessary by means of the following formula:

$$\text{width of belt} = .7 \times \frac{W}{S'} \qquad \textbf{(18)}$$

where W = output of generator in watts.

Applying this to the 100-kilowatt machine, we get

$$\text{width of belt} = .7 \times \frac{100,000}{4,500} = 15.5 \text{ inches}$$

We will allow $\frac{3}{4}$ inch on each side of the belt, thus making the face of the pulley 17 inches wide. Fig. 38 shows a pulley $28\frac{1}{2}$ in. × 17 in. suitable for this machine. The pulley is provided with one set of arms only, as the face is not very wide. Setscrews are provided to prevent the pulley working endwise on the shaft.

CONNECTIONS

80. The **electrical connections** for alternators have already been shown diagrammatically; it is now necessary to see how these are carried out on the machine. We will first consider the connections suitable for a single-phase compound-wound machine of the type designed. Fig. 39 represents the connections of such a machine. T and T' are the two terminals of the armature winding, one of which is connected to one collector ring by means of the stud *a*. The other terminal T' is connected to one side of the rectifier by the stud *b*, the other side of the rectifier being connected to the remaining collector ring. If a revolving shunt is used across the rectifier, it is necessary to have another connection stud, shown by the dotted line. The revolving shunt is then connected between this stud and *b*, thus placing the shunt across the rectifier and allowing a certain portion of the total current to flow by without being rectified. The line wires lead from the two collector rings, and the rectifier brushes are connected to the series-field by means of the connection boards *c*, *c*. The connections between the series-field, armature, rectifier, and collector rings shown in Fig. 39 are those that are used on the General Electric Company's machines of this type. The Westinghouse Company uses a different arrangement for supplying the rectified current to the series-coils, which is

shown in Fig. 40. In this case the terminal T is connected to one end b of the primary $a\ b$ of a small transformer. The other end of this primary connects to the collector ring, as shown, so that all the current flowing through the armature passes through this coil. The secondary $c\ d$ of this transformer connects directly to the two sides of the rectifier, which, in turn, connects to the series-field by

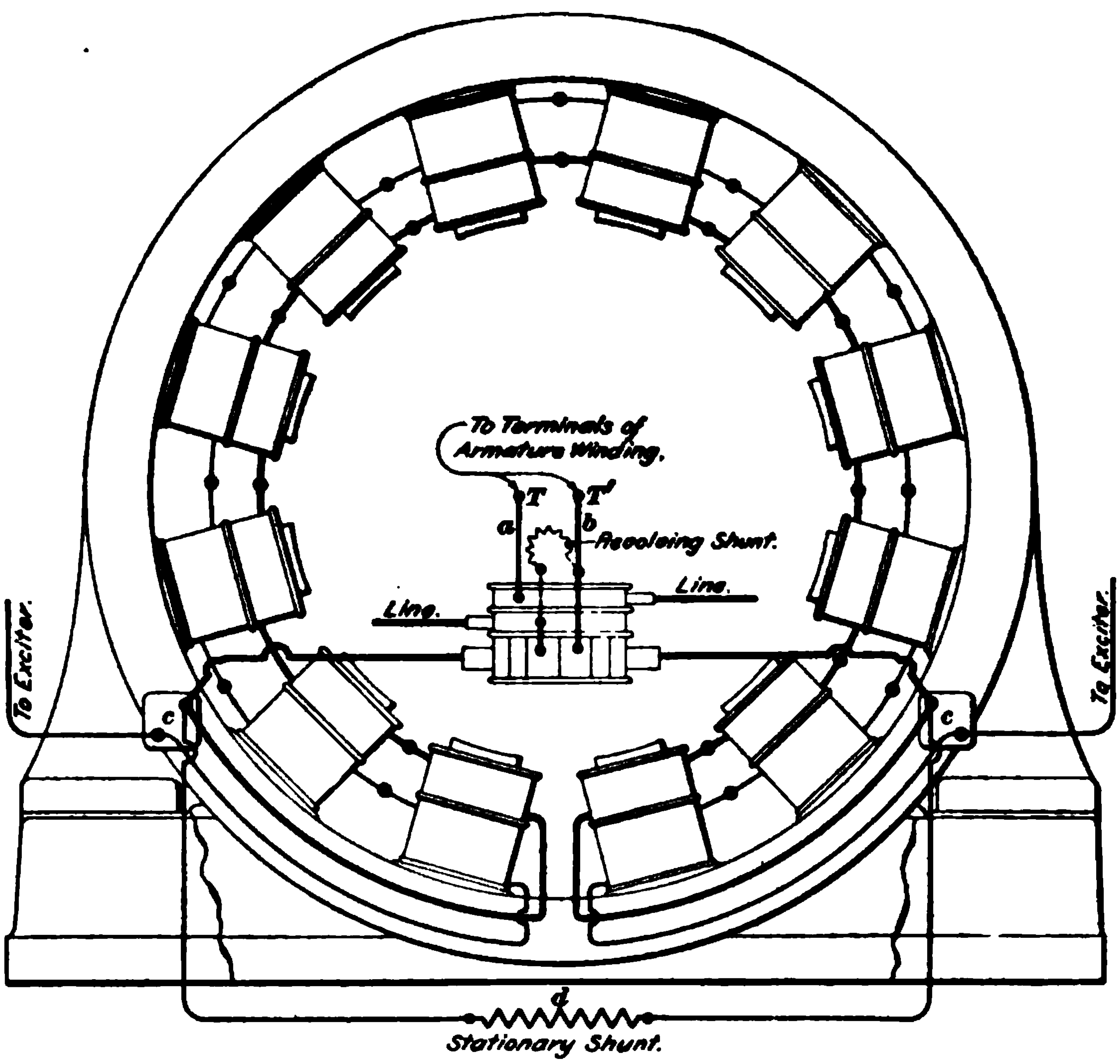


FIG. 39

means of the brushes. The other collector ring is connected directly to the winding, as shown. In this case it is seen at once that there is no electrical connection between the armature and the series-coils, the latter being supplied by an induced current from the secondary $c\ d$. This transformer, which is usually quite small, must, of course, revolve with the armature, and in some of the smaller

machines the spokes of the spider form the core of the transformer. The use of this transformer renders the insulation of the series-coils easier, because it separates the armature connections entirely from the field.

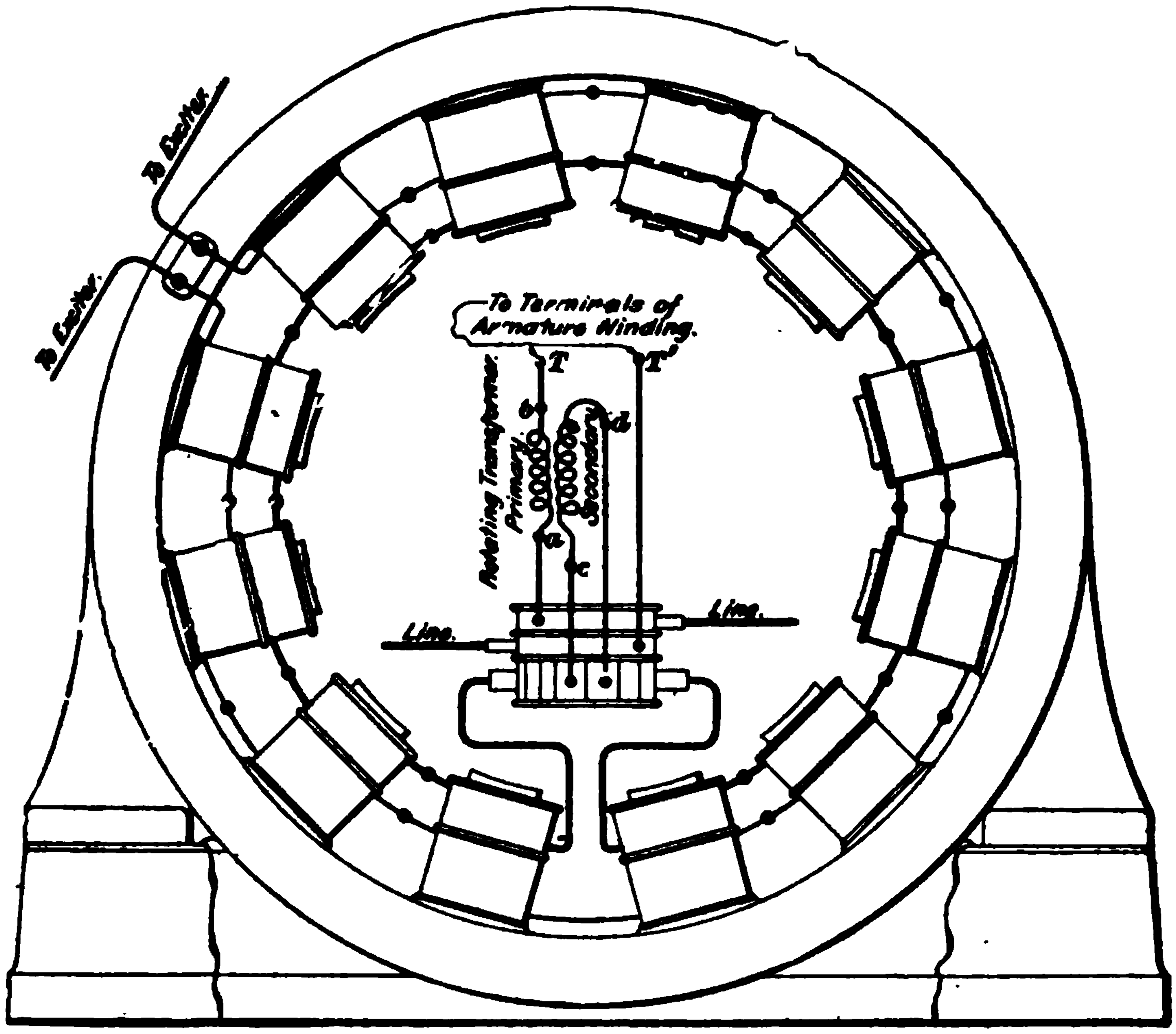


FIG. 40

81. The connections for the field coils vary little in different makes of machines, so we will take those shown in Fig. 39 as a typical case. The windings of the field coils are connected up so as to make the poles alternately N and S. Care must be taken that the series-coils are not connected in such a way as to oppose the separately excited coils instead of aiding them. The terminals of the separately excited coils are led directly to the connection boards *c*, *c*. The terminals of the series-coils are also led to the same boards, and from there connected to the rectifier brush-holder studs by means of flexible cables. The stationary

shunt *d* is connected to the same terminals on the connection boards as the series-field. This shunt may be attached to the machine or placed on the switchboard; it is usually made up of German-silver wire or ribbon of such size that it will not overheat with the maximum current it may be called on to carry. The connections and winding of the separately excited coils are generally the same, no matter what the current output or voltage of the machine may be. The series-connections may, however, be varied somewhat in machines with different current outputs. When the current output is large, the series-coils are sometimes grouped in two sets connected in parallel, thus reducing the current in the field conductor and allowing the use of smaller and more easily wound wire. For example, the 100-kilowatt machine designed had a full-load current output of 45.4 amperes at 2,200 volts; if the same machine were built for 1,100 volts, the current output would be 90.8 amperes at full load. In the first case the series-field was designed to carry 32 amperes; in the second case it would have to carry 64 amperes. Generally, we would wish to get the same number of ampere-turns on each pole in either case; so, instead of winding the coils with half as many turns of wire, large enough to carry double the current, we can connect the six upper coils in series and connect them in parallel with the six lower coils, which are also connected in series. This will keep the current in the coils the same, although the line current is doubled. This is often done in practice, as it allows the coils that were designed for a machine of certain voltage to be used for a machine of half that voltage without changing the coil winding in any way.

82. The line connections are usually made directly to the collector-ring studs when the machine is provided with a revolving armature. When the armature is stationary, the armature terminals are simply run to a connection board, to which the lines are attached. Fig. 41 shows a simple form of connection board, suitable for the connections shown in Fig. 39. The base *a* should have high

insulating properties, and is preferably made of porcelain, or hardwood treated with oil. Slate is not a good material for this purpose, because it is liable to contain metallic veins. Cable terminals *c* are provided for the connections, and these are held in place by screws *d* passing through

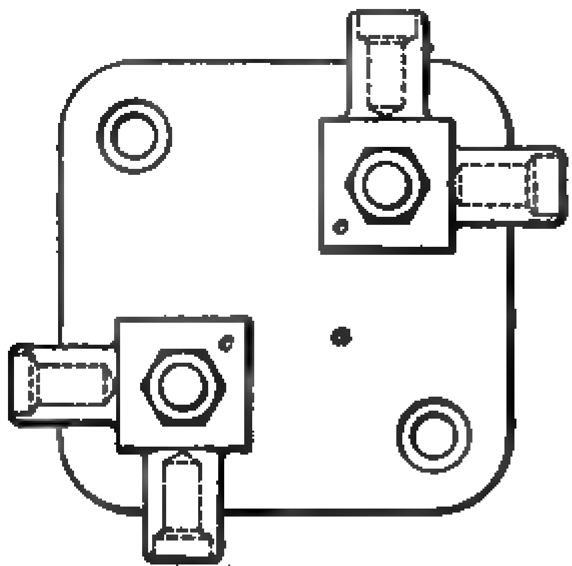


FIG. 41

from the back of the base. These screws are well countersunk, and the holes filled in with insulating compound, in order to obviate any danger of the connections becoming grounded on the frame of the machine. The nuts *e* clamp the terminals firmly in place against the brass blocks *b*.

83. Connections between the individual field coils are usually made by means of small brass connectors similar to those shown in Fig. 42. Three of the commoner forms are here shown. They all consist of two brass plates *e*, *f* provided with grooves to receive the ends of the coils, and clamped together by screws, as shown. The ends of the coils usually consist of heavily insulated wire brought out from the winding. In some cases where the coils are wound with copper strip, connection between the coils is made by simply clamping the ends of the strip together between brass washers.

84. Special reference has not been made to the design of fields for two- and three-phase machines, because there is very little difference between such fields and the one

worked out for the single-phase machine. The only difference might be a slight change in the series-winding and the

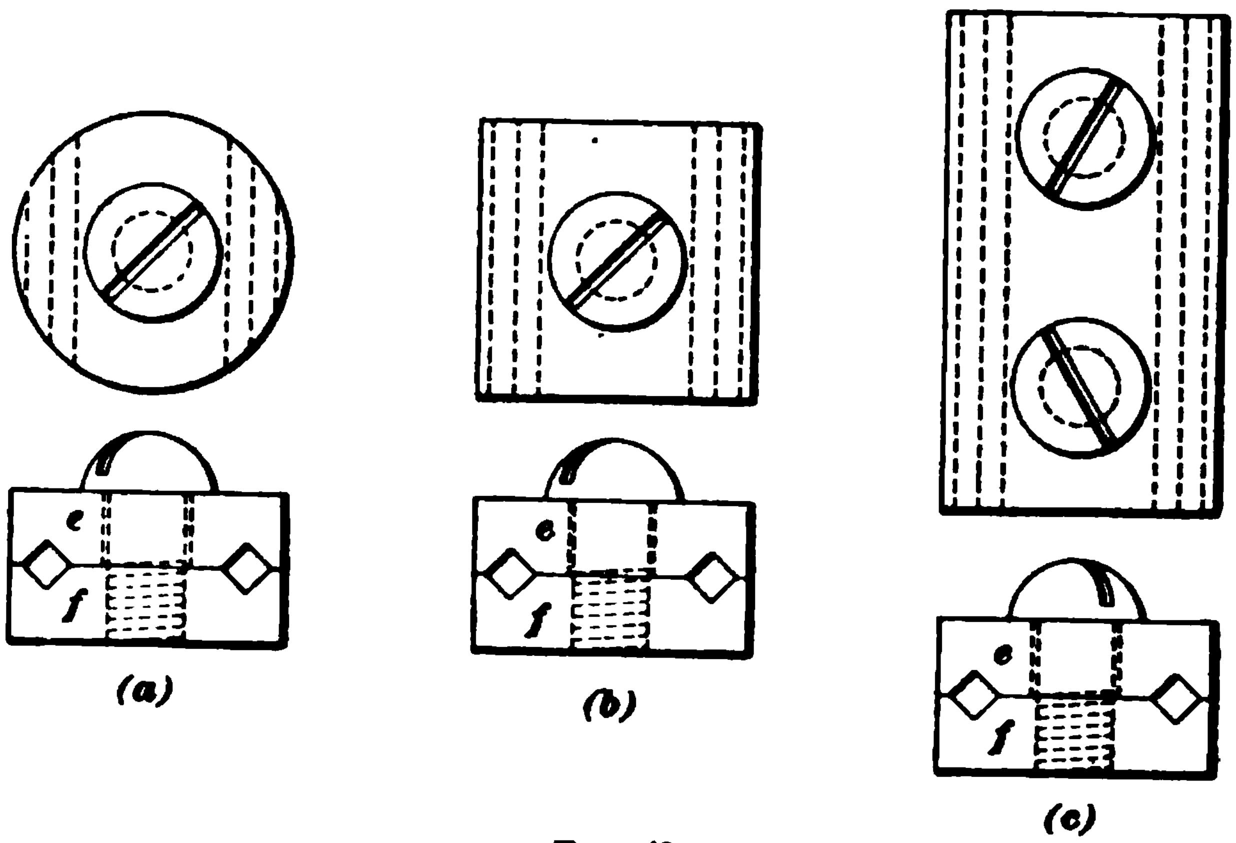


FIG. 42

connections to the rectifier. The winding of the separately excited coils would be the same, because the exciter voltage would not be changed, and all three fields were assumed to furnish the same magnetic flux.

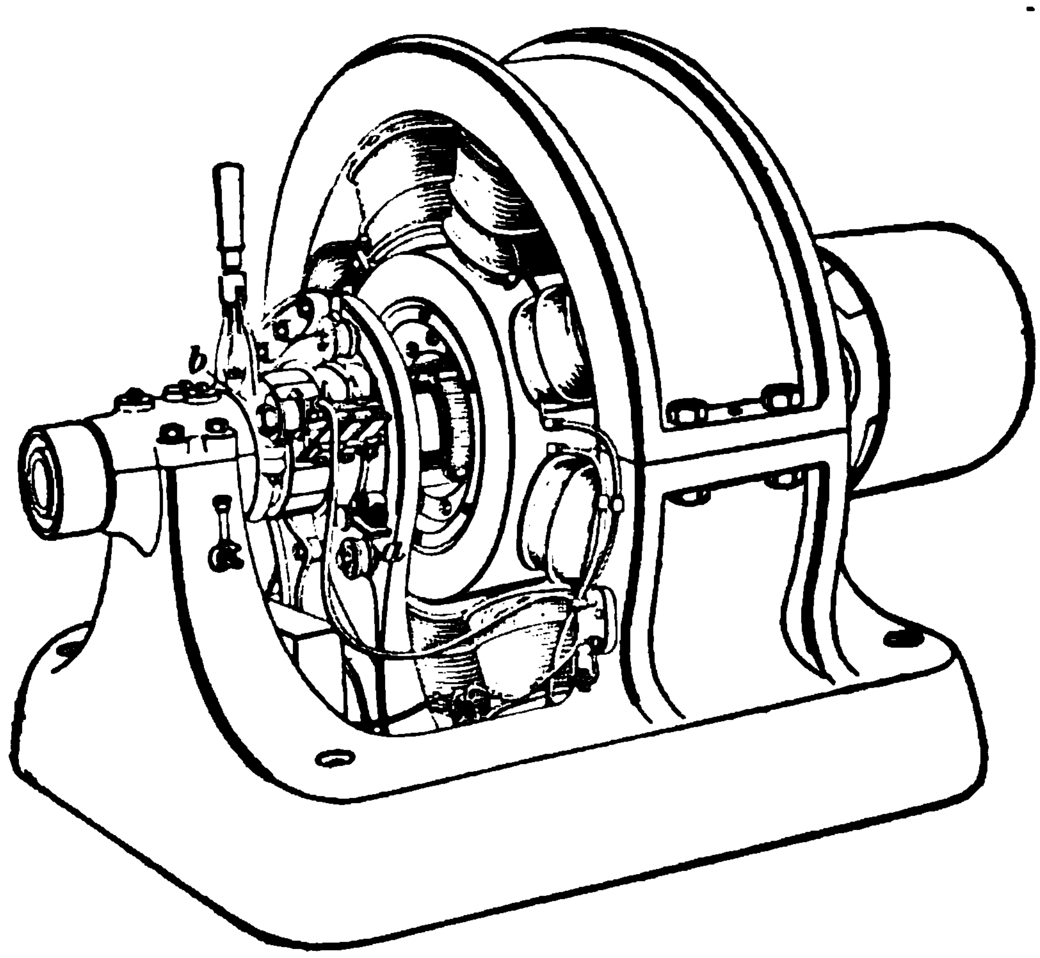


FIG. 43

85. Fig. 43 shows an assembled compound-wound machine with stationary field and revolving armature, such

as we have worked out. The lower half of the yoke is in this case cast with the bed, and the yoke itself is provided with flanges. The collector-ring brushes are here shown mounted on a stand *a*, and the rectifier brushes are carried on a rocker *b* mounted on the inside end of the bearing. The arrangement of cables, connection boards, etc., will be readily seen by referring to the figure. Fig. 44 shows a large alternator designed to run at low speed. This machine is provided with a stationary armature and revolving field, the collector rings shown on the shaft being used to convey the exciting current into the field coils.

FIG. 44

DESIGN OF ALTERNATING-CURRENT APPARATUS

(PART 3)

TRANSFORMERS

1. It has been shown that a certain amount of loss always occurs in a **transformer** so long as its primary is connected to a source of E. M. F.; this loss may be divided, for convenience, in two parts, namely, *iron losses* and *copper losses*. The **iron losses** are those that occur in the iron core of the transformer, and are due to hysteresis and eddy currents. They are practically constant for all loads, because they are dependent on the magnetic density in the core, and this changes but little from no load to full load. The **I^2R loss,** or **copper loss,** in the coils increases with the load. The combined effect of these losses is to heat up the coils and core, so that the amount of power that a transformer is capable of delivering is limited by the heating effect. The transformer could therefore be loaded until the coils reached the maximum temperature that the insulation on the wire could stand without injury; any further increase in load would result in the transformer being eventually burned out. Aside from the danger of overheating, a transformer should not be worked much beyond its rated load, because of the falling off in efficiency. If the load is forced too high, the $I^2 R$ loss becomes excessive, and

the transformer works uneconomically, even if it does not happen to overheat.

Overloading a transformer also causes a falling off in the secondary voltage, which is very objectionable if the transformer is used for lighting work.

2. A transformer should be so designed that it will do the work of transforming the current with the least possible cost. This means that the efficiency must not only be high at full load, but that it should also be high throughout a

Transformer efficiency curve.
FIG. 1

wide range of load. Fig. 1 shows the efficiency curve for a transformer of good design. It will be noticed that the efficiency increases very rapidly at first, being as high as 60 per cent. with only one-sixteenth of the full load on the secondary. The efficiency varies but slightly between one-fourth load and full load, and when the transformer is overloaded, the efficiency begins to fall off. A transformer is seldom worked at its full capacity all the time; hence, it is important to have a good efficiency through a wide range of load, as shown by the curve. The efficiency can be made

high by employing anything that will keep down the losses; but for a transformer of given size, the efficiency cannot be increased beyond a certain point without greatly increasing the weight and cost. For example, the $I^2 R$ loss might be made very small by using a large cross-section of copper, but this would necessitate a large winding space, thus increasing the bulk of the transformer and making the core heavy. Increasing the efficiency beyond a certain point is attained only by a large increase in cost, and a transformer may, in general, be said to be well designed when it gives the highest all-day efficiency consistent with an economical distribution of iron and copper. The curve, Fig. 2, shows the relation between output and full-load efficiency that should be attainable in good transformers. The efficiency

Relation between efficiency and output of transformers.

Fig. 2

increases rapidly with the output for transformers of small size, but changes slowly after outputs of 4 or 5 kilowatts are reached. Some very large transformers have an efficiency as high as 98 per cent., or slightly over, but it is only in transformers of large size that such a high efficiency is reached.

TRANSFORMER CORES

3. Transformer cores have been made in a large number of different shapes, but the two most generally used types are the *core* and *shell* varieties. Good transformers may be designed using either the core or shell construction, and large numbers of both styles are in common use. Great care should be taken in the selection of the iron for transformer cores. It should be borne in mind that the hysteresis loss goes on continuously, whether the transformer is loaded or not, and that everything possible should be done to keep this loss small by using only the best quality of core iron. The stampings should be about 12 or 14 mils thick for 125-cycle transformers, but may be slightly thicker than this for transformers of low frequency. The oxide on the iron, with the addition of a paper sheet at intervals along the core, is usually sufficient to insulate the sheets from each other. Some makers coat the plates with an insulating varnish or japan and do not depend on the oxide film.

HEATING OF TRANSFORMERS

4. Since the efficiency of transformers is generally high, the energy lost in them is small, and in transformers of ordinary size there is generally enough radiating surface to get rid of the heat generated. Transformers up to 50-kilowatt capacity can usually be made with sufficient ventilation to get rid of the heat generated, but for larger sizes it is often necessary to use special cooling arrangements. Air blasts are frequently used to carry the heat away from the core and windings of large transformers. Sometimes the core and windings are immersed in oil kept cool by water circulating in pipes. Transformers of smaller size are usually designed so that the case may be filled with oil. This helps to give the windings good insulation, and keeps down the temperature by conducting the heat from the windings and core to the outside casing. The student

should bear in mind that while these special devices are in many cases necessary to get rid of the heat, it does not follow by any means that the transformer is inefficient; on the contrary, the efficiency is usually very high, and these devices are necessary only because the transformer of itself does not present enough radiating surface to get rid of the heat. No definite rules can be given as regards the number of watts that can be radiated per square inch of core or case surface that will apply to all types of transformers. This radiation constant varies widely for transformers of different sizes and forms, but unless the efficiency is very low, the dimensions of transformers under 40 or 50 kilowatts are usually such that they can get rid of the heat generated without undue rise in temperature.

MAGNETIC DENSITY IN CORE

5. Transformer cores are worked at low magnetic densities in order to keep down the core losses and magnetizing current. The hysteresis loss is proportional to the frequency, and the eddy-current loss to the square of the frequency; hence, for an allowable amount of core loss it follows that higher magnetic densities can be used with low-frequency than with high-frequency transformers. For 60-cycle transformers, the maximum value of the magnetic density may be taken from 28,000 to 32,000 lines per square inch. For 125-cycle transformers, the density may be from 19,000 to 21,000 lines per square inch. The densities in individual cases may vary from the above, but the average values used are generally within the limits given.

6. The allowance of copper per ampere in the primary and secondary coils should be large, in order to keep down the copper loss and prevent overheating. The coils are usually heavy, and it is also important to have a liberal cross-section of copper, in order to prevent overheating. The cross-section per ampere should be about the same both for primary and secondary coils. When the core type is

used, there is usually room for a liberal cross-section of copper, but in the shell type the winding space is more restricted, and the coils cannot be made very large without considerably increasing the bulk of the iron core. The number of circular mils allowed per ampere varies greatly in transformers of different makes and sizes. In general, the allowance should not be less than 1,000 or 1,200 circular mils per ampere, and in many of the later types of transformers the allowance may be as high as 2,000, or over.

ARRANGEMENT OF COILS AND CORE

7. The **arrangement of coils and core** has already been described for two of the common types. The core type can be usually arranged so that it can be taken apart and the coils slipped off in case repairs are necessary, while the shell construction usually requires the removal of each plate before the coils can be reached. Transformers have been made with the core built in sections, as shown in Fig. 3. In this case the upper part *a* is built up separately, and forms a cover that can be removed from the main part of the core when it is desired to get at the coils. This construction is, however, objectionable, because it introduces small air gaps into the magnetic circuit at *b*, *b*, thereby increasing the magnetic reluctance. In designing transformer cores, every effort should be made to have the magnetic circuit continuous. Fig. 4 shows an arrangement of coils and core suitable for a transformer of large size. The stampings *a* and *b* are cut as shown, the joints being at *c*, *d*, and *e*. As the core is piled up, these joints are staggered, as shown by the dotted lines, thus making the iron path for the lines practically continuous and doing away largely with the bad effects of the joints. The primary and secondary coils are wound in a number of sections, each consisting of a flat coil, these sections being sandwiched, as shown, in order to reduce the magnetic leakage between them. Splitting up the coils in this way also makes it easier to insulate the transformer for

high voltages, because it cuts down the voltage across any one of the coils. The coils are usually separated from each

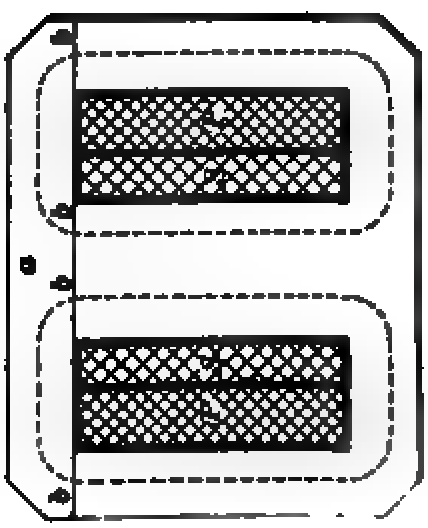


FIG. 3

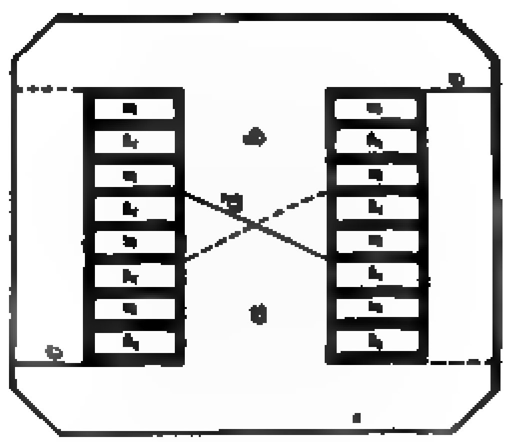


FIG. 4

other by a built-up sheet of mica, or other material having high insulating properties. Large cores are frequently

provided with ventilating ducts between the laminations, as shown at *f*. The laminations are held apart by brass castings, and the channels so formed allow air to circulate through the core, the whole construction being similar to that used for ventilated armature cores. Fig. 5 shows another arrangement of coils and core that also makes use of thin flat coils. In this case the stampings *a* and *b* surround one side of the coil only, a separate set of stampings

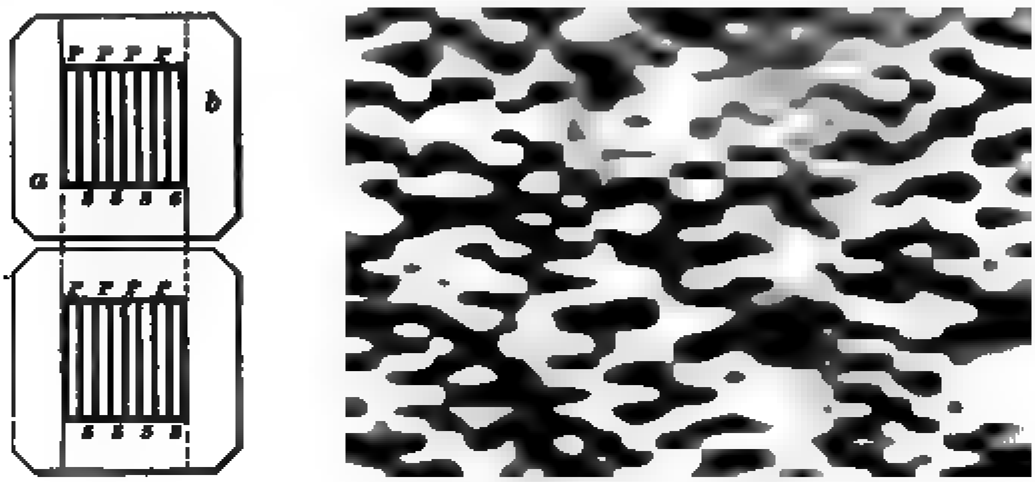


FIG. 5

being used to form the magnetic circuit around the other side. This is the construction used by the Westinghouse Company for several of their larger transformers. The projecting ends of the coils *c* are frequently spread out like a fan, so as to allow air to circulate freely between them.

WINDING AND INSULATION OF COILS

8. Since transformer coils are usually of simple shape, they can generally be lathe-wound and thoroughly insulated. High insulation is of great importance in transformers, and every precaution should be taken to see that the primary and secondary coils are not only well insulated from the core, but also from one another. Fig. 6 shows the shape of a primary coil commonly used for shell transformers. The coils must withstand a high impressed line E. M. F., and the voltage between layers may therefore be considerable

Insulation *i* should be placed between each layer; this may be composed of oiled linen tape or other good insulating material. The outside of the coil is heavily taped and afterwards treated with insulating varnish and baked. Additional insulation in the form of mica and paper, or in some cases oiled hard-wood pieces, is placed between the coils and the core. The insulation between primary and secondary should be specially good. Some makers allow a clear air space between the coils, in addition to the insulation on

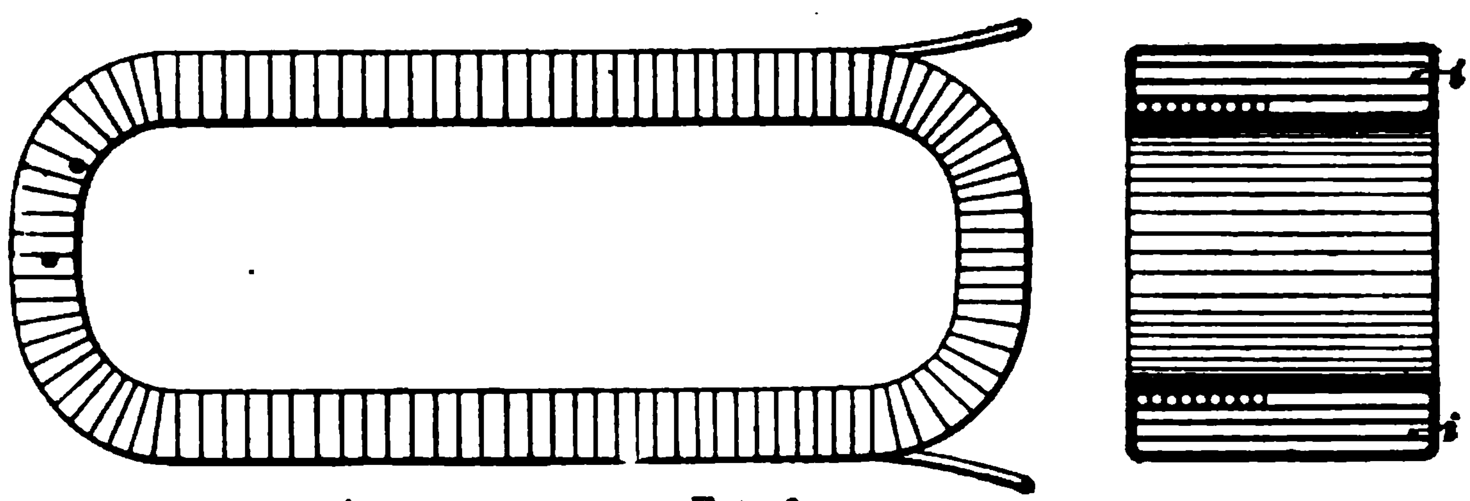


FIG. 6

the coils themselves. If connection should be established between the primary and secondary, and there should happen to be a ground on the primary mains, a difference of potential would exist between the secondary service wires and the ground that would be equal to the primary voltage. Such a difference of potential between the service wires and the ground would be very dangerous to life; hence, the importance of thorough insulation between the primary and secondary.

9. The conductor used for the primary winding usually consists of copper wire, except in large transformers, where copper strip may be used to advantage. For the secondary, a conductor of large cross-section is usually required, because the secondary voltage is generally low and the current correspondingly large. For transformers of moderate output, the secondary conductor can generally be made of a number of wires in multiple. In most large transformers, the secondary conductor is made up of copper strip. Fig. 7 shows a flat secondary coil made up in this way. Such a

coil would be suitable for the transformer shown in Fig. 5. The details of construction and method of calculating the

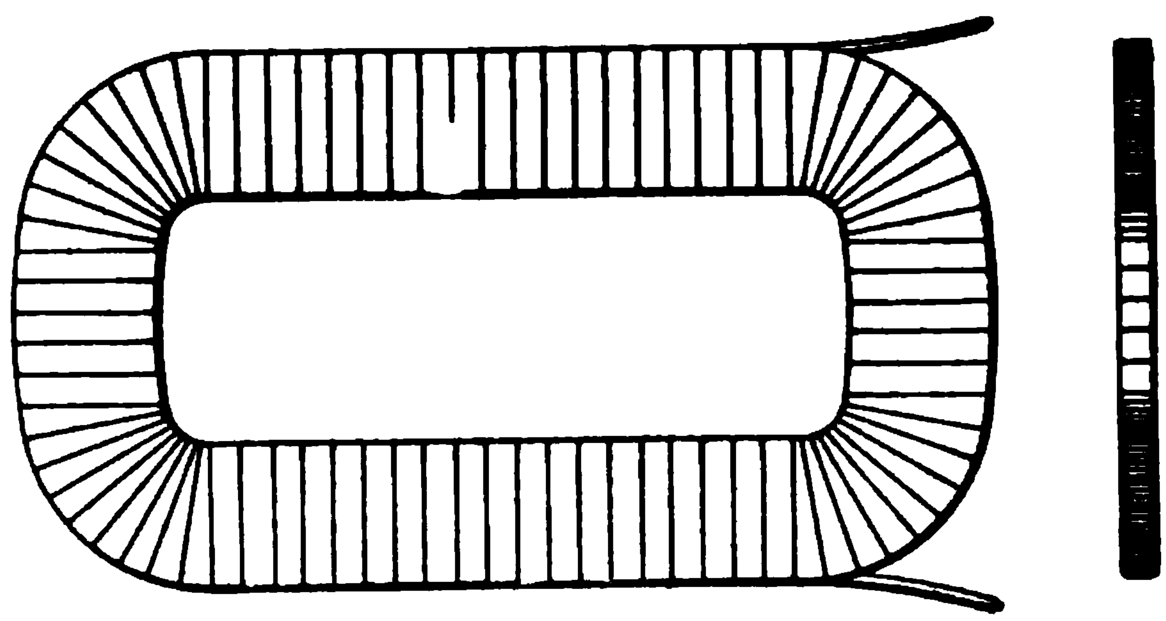


FIG. 7

different parts will be best understood by working out an example. We will therefore take up the design of a transformer of the core type such as would be suitable for lighting work.

DESIGN OF 8-KILOWATT TRANSFORMER

10. In starting out to design a transformer, the following quantities are either known or assumed: Useful secondary output in kilowatts (K. W.); primary voltage (E_p); secondary voltage (E_s); frequency of system on which the transformer is to be operated (n). For ordinary lighting transformers, E_p is in the neighborhood of 1,000 or 2,000 volts; E_s, 50 or 100 volts; and n, 60 or 125 cycles per second.

11. We will take for an example an 8-kilowatt transformer of the core type to be designed for 2,000 volts primary and 50 or 100 volts secondary, the secondary being wound in two coils, which may be connected in parallel for 50 volts or in series for 100 volts. The frequency will be taken as 60. A good transformer of this output should have a full-load efficiency of 96.8 or 96.9 per cent.; consequently, in designing it we should aim to keep the losses

down to such an amount that the efficiency will be, say, 96.8 per cent. We have

$$\text{efficiency} = \frac{\text{watts output}}{\text{watts input}}$$

Hence, for an output of 8,000 watts, the input will be

$$\text{input} = \frac{8{,}000}{.968} = 8{,}264 \text{ watts}$$

The total loss at full load, therefore, should not exceed 264 watts. This total loss is made up of three parts, namely, the losses due to the resistance of the coils, hysteresis, and eddy currents. The I^2R loss and the core losses should be about equally divided; that is, the copper loss should be about equal to the sum of the hysteresis and eddy-current losses. If the transformer is used only a short time during each day, it might be well to allow the I^2R loss to be a little larger than the core losses, but the above relation holds approximately correct for well-designed transformers. In the present case, we will aim at making the copper loss, say, 140 watts, and the core loss 124 watts. This division of the losses should give a satisfactory transformer for lighting work.

DETERMINATION OF CORE VOLUME

12. Since the transformer is to operate on a 60-cycle system, we will take 30,000 lines per square inch as a fair value for the maximum magnetic density in the core. At this frequency and density, there will be a definite amount of loss per cubic inch of iron in the core, depending on the quality of the iron used. We will assume that the curve A, Fig. 2, Part 1, represents the quality of the iron in this respect. From this curve, we find that the loss per cubic inch per 100 cycles at a density of 30,000 is about .25 watt. The loss at 60 cycles will therefore be $\frac{60}{100} \times .25 = .15$ watt.

The total core loss is to be 124 watts. This is the loss due to hysteresis and eddy currents combined. The eddy-current loss should be quite small if the core is properly

laminated: hence, we will take the hysteresis loss alone as 110 watts, and allow 14 watts for the loss due to eddy currents. If the loss per cubic inch is .15 watt, then the volume of iron in the core will be $\frac{110}{.15} = 733$ cubic inches.

DIMENSIONS OF CORE

13. The volume of iron in the core has now been determined, and it remains to proportion the core itself. Fig. 8 shows the style of core used for this type of transformer, and in proportioning it due regard must be had to the windings that are to be placed on the cores c, c. We will make the core square in cross-section, with the corners chamfered slightly, as shown in the figure. If the cross-section $a \times a$ is made very small, the cores will be long and thin, the magnetic flux Φ will be small, and the coils will have to be provided with a large number of turns to generate the required E. M. F. Long cores also give rise to a long magnetic circuit, thus increasing the magnetizing current. On the other hand, if the cores are made very short,

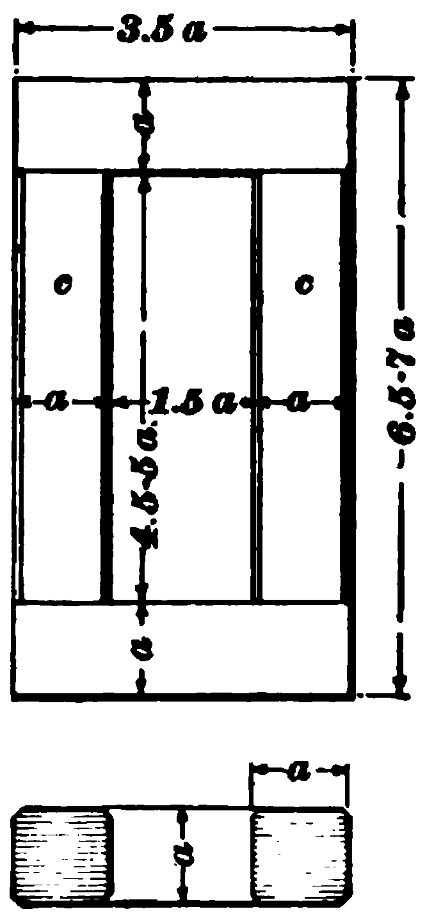


FIG. 8

the wire will have to be piled up deep, in order to get it into the winding space, and the yokes across the ends will have to be made longer. Deep windings also mean a long length of wire for a given number of turns, resulting in a large amount of copper. The best proportions to be given to the core are therefore largely a matter of experience. For preliminary dimensions, we will use the proportions indicated in Fig. 8, all the dimensions being here expressed in terms of the thickness of the cores. We will make the height of the core $= 7\,a$. The volume of the core will then be

$$V = (2 \times 3.5\,a + 2 \times 5\,a)\,a^2 \qquad (1)$$

a^2 being the area of cross-section and $5a$ the distance between the yokes. This gives

$$17a^2 = V = 733 \text{ cubic inches}$$

$$a = \sqrt[3]{\frac{733}{17}}$$

This makes a just about $3\frac{1}{2}$ inches. This is the value of the thickness of the core if it were solid iron. Part of the cross-section is, however, taken up by insulation between the plates, and the corners are cut off slightly, so we will make the core $3\frac{5}{8}$ inches square. The other dimensions follow from this, so we will take the dimensions given in Fig. 9 as a basis for further working out the design. The distance between the inside edges of the cores will be $5\frac{7}{16}$ inches, and the space between the yokes available for the windings will be $18\frac{1}{8}$ inches.

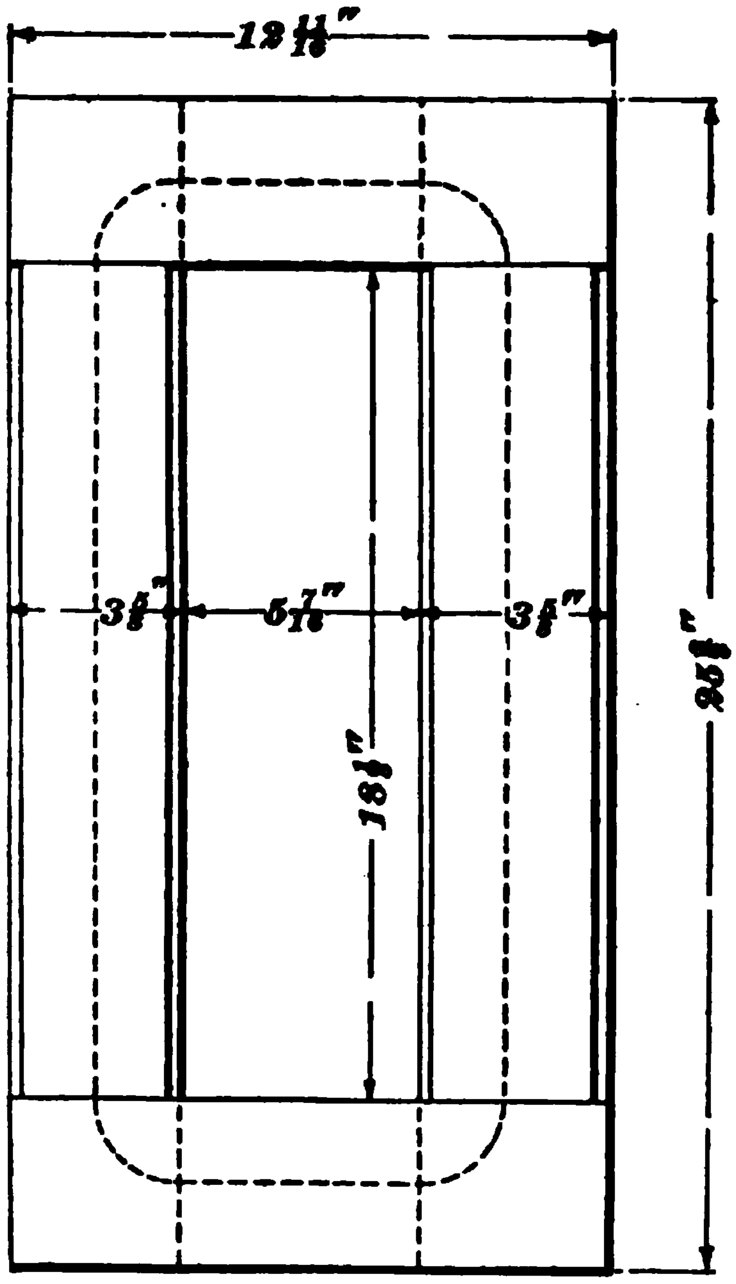


FIG. 9

DIMENSIONS OF CONDUCTORS

14. We will wind the secondary coil next the cores, and place the primary over it. The secondary current at full load will be

$$\frac{\text{secondary watts}}{\text{secondary volts}} = \frac{8{,}000}{100} = 80 \text{ amperes} \qquad (2)$$

The secondary coil will be wound in two sections, one section being placed on each core. Each section will have a sufficient number of turns to generate 50 volts, and the

conductor will be capable of carrying 80 amperes. If an output of 100 volts and 80 amperes is required, the coils may be connected in series and their E. M. F.'s added. If an output of 160 amperes at 50 volts is desired, the coils may be connected in parallel. In either case, the full-load current in the conductor will be 80 amperes. In this type of transformer, a large cross-section is usually allowed per ampere, because there is plenty of room for the coils, and the number of turns is usually large. We will therefore allow 2,000 circular mils per ampere to obtain the approximate size of the conductor. We then have

Circular mils cross-section of secondary conductor = 80 × 2,000 = 160,000 circular mils.

Six No. 6 B. & S. wires in parallel will give 6 × 26,250 = 157,500 circular mils. We will make up the secondary conductor, as shown in Fig. 10, using six bare wires in multiple and covering the whole with a cotton insulation having a double thickness of 20 mils. The bare diameter of the wire is .162 inch; hence, the width of the conductor over all will be 2 × .162 + .02 = .344 inch. The height of the conductor will be 3 × .162 + .02 = .506 inch.

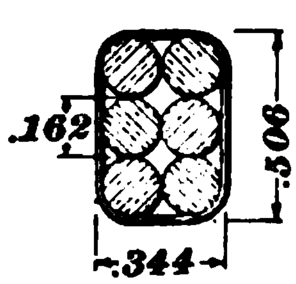


FIG. 10

15. The watts supplied to the primary at full load are 8 264. Hence, the approximate primary current will be

$$\frac{\text{primary watts}}{\text{primary volts}} = \frac{8,264}{2,000} = 4.132 \text{ amperes} \qquad (3)$$

The primary current at full load will be very nearly in phase with the E. M. F.; or, in other words, the power factor will be very nearly 1. The magnetizing current should be quite small, so that the primary current at full load will be but slightly larger than the above amount. We will call the full-load primary current 4.25 amperes, in order to allow a little for the magnetizing current. Allowing the same cross-section per ampere in the primary as in the secondary, we get

Circular mils of primary conductor $= 4.25 \times 2{,}000 = 8{,}500$ circular mils.

A No. 11 B. & S. wire has a cross-section of 8,234 circular mils, which is nearly the number required. The diameter of this wire over the insulation may be taken as .101 inch.

CALCULATION OF PRIMARY AND SECONDARY TURNS

16. The primary coil has to be provided with a sufficient number of turns to generate a counter E. M. F. equal and opposite to that of the mains. The impressed E. M. F. is equal and opposite to the resultant of the E. M. F. generated by the primary and the E. M. F. necessary to overcome the resistance of the primary. The drop through the primary at no load due to the ohmic resistance is so small that it may be neglected in comparison with the E. M. F. that is generated by the primary coil, so that we may take the E. M. F. so generated as equal numerically to the impressed E. M. F. The number of turns required to set up this E. M. F. will depend on the magnetic flux Φ that threads through the turns. The maximum magnetic flux through the coil will be

$$\Phi = \mathbf{B}\ \text{max.} \times A \qquad (4)$$

where **B** max. is the maximum value that the magnetic density reaches during a cycle, and A is the area of cross-section of iron in the core on which the coil is wound.

In this case, **B** max. is 30,000 lines per square inch, and the area of cross-section of the iron is $3\frac{1}{2} \times 3\frac{1}{2} = 12.25$ square inches; hence,

$$\Phi = 30{,}000 \times 12.25 = 367{,}500 \text{ lines}$$

Taking the E. M. F. generated in the primary as the equal and opposite of the line voltage, we may write

$$E_p = \frac{4.44\ \Phi\ T_p\ n}{10^8} \qquad (5)$$

where Φ = maximum value of the magnetic flux through the core;

T_p = number of turns on primary coil;

n = frequency (cycles per second);

E_p = impressed primary voltage.

Applying this to the present example, we have

$$2,000 = \frac{4.44 \times 367,500 \times T_p \times 60}{10^8}$$

or $$T_p = \frac{2,000 \times 10^8}{4.44 \times 367,500 \times 60} = 2,042, \text{ nearly}$$

We will therefore provide the primary coil with, say, 2,040 turns, and place 1,020 on each of the cores, as this number will give an even number of turns on each coil. Dropping two turns would not appreciably affect the working of the transformer, as the magnetic density would have to be increased but very slightly to make up for the difference.

17. The number of secondary turns T_s will be

$$T_p \times \frac{E_s}{E_p} \qquad (6)$$

where E_s is the secondary voltage, since the turns must be in the same ratio as the voltages generated. This will give for the present case

$$2,040 \times \frac{100}{2,000} = 102 \text{ turns}$$

The total number of secondary turns will therefore be 102, or there will be 51 turns on each coil, using the conductor shown in Fig. 10.

ARRANGEMENT OF PRIMARY AND SECONDARY COILS

18. The coils will be arranged on the core as shown in the section through the coils and core, Fig. 11. The coils are here shown circular in cross-section; very often they are approximately rectangular in shape, the secondary being

wound directly on the core and the wooden pieces *a*, *a* omitted. In the larger sizes of transformer of this type, cylindrical coils are commonly used. The secondary will be wound next the core, in order to make the length of the heavy secondary conductor as short as possible. The coil may be held firmly in position by oiled hardwood blocks *a* placed between it and the iron core *b*.

FIG. 11

The diameter of the coils could be made somewhat less by chamfering the corners more than shown, but this would decrease the cross-section of iron, so that very little would be gained in the end. Both coils are heavily insulated with linen tape, and provision is made for a clear space of $\frac{3}{16}$ inch between the primary and secondary. The length of the cores between the yokes is 18¼ inches (see Fig. 9). Each secondary coil contains 51 turns The breadth of each turn is .344 inch, so that 51 turns will take up a length along the core of $51 \times .344 = 17.5$ inches. The secondary coil can therefore be made up of one layer of 51 turns of the conductor shown in Fig. 10. This arrangement will allow about $\frac{3}{16}$ inch clearance at each end between the secondary winding and the yoke, in addition to the taping. The arrangement of this winding will be readily understood by referring to the section of the coils shown in Fig. 13. The mean diameter of the secondary coil will be 5½ inches and the mean length of a turn 17.28 inches.

19. The primary coil is placed over the secondary, as shown in Fig. 11. The space of $\frac{3}{16}$ inch is allowed to insure

good insulation between the coils; sometimes a mica insulating shield is placed between the coils. In case the transformer is immersed in oil, the film of oil between the coils forms an insulating layer that is not easily broken down. We will make the primary coil slightly shorter than the secondary, and adopt a clear winding space, say, $17\frac{1}{4}$ inches in length. This will remove the high-tension primary windings a little farther from the yokes and avoid danger of breakdown. The diameter of the primary conductor over the insulation is .101 inch; hence, in a layer $17\frac{1}{4}$ inches long we can place $\frac{17.25}{.101} = 170$ turns, nearly. We must place 1,020 turns on each coil, so that we can arrange the winding by using six layers of 170 turns per layer. The two primary coils are connected in series across 2,000-volt mains; hence, the pressure across each coil will be 1,000 volts, and there will be 166 volts generated in each layer. The pressure tending to break down the insulation between the beginning of the first layer and the end of the second will therefore be the maximum value corresponding to an effective pressure of 333 volts. It is necessary, therefore, to insulate each layer from the one next to it, and particular care should be taken at the ends of the coil, where a breakdown between layers is most liable to occur. We will allow 20 mils for insulating tape between each layer and $\frac{1}{16}$ inch all around for the outer taping on the coil. This will make the thickness of the primary coil $6 \times .101 + 5 \times .020 + \frac{1}{8} = .831$ inch.

The mean diameter of the primary coil will be about $7\frac{3}{8}$ inches, and the mean length of a primary turn 23.17 inches.

20. All the essential dimensions of the transformer have now been determined. With the primary winding calculated above, the outside diameter of the primary coil will be about $8\frac{1}{8}$ inches. The distance from center to center of cores is $5\frac{7}{16} + 3\frac{5}{8} = 9\frac{1}{16}$ inches, so that there would be a space between the coils of $\frac{15}{16}$ inch, and the design is suitable as far as the accommodation of the windings goes.

EFFICIENCY

21. In designing the transformer, we aimed at securing a certain **efficiency,** and so proportioned the core that the hysteresis loss should not exceed 110 watts. The design has been worked out, and it is found that the windings obtained can be accommodated on this core. It now remains to be seen whether the copper loss in these coils is within the allowable amount. If the copper loss is excessive, we must remodel the design of the coils so as to bring it to nearly the allowable amount. In order to calculate t' copper losses in the primary and secondary, we must determine their resistance.

22. In calculating the resistance of the coils, we will take the resistance of a mil foot of copper as 12 ohms, as it is the hot resistance that we must consider. Since there are 51 turns on each secondary coil, and the length of each turn is 17.28 inches, the resistance of each coil will be

$$R_p = \frac{\text{total length in inches}}{\text{area in circular mils}} = \frac{51 \times 17.28}{157,506} = .0056 \text{ ohm}$$

and the resistance of the two coils in series will be .0112 ohm.

The loss in the secondary at full load will therefore be

$$I_s^2 R_s = (80)^2 \times .0112 = 71.68, \text{ say, } 72 \text{ watts} \qquad (7)$$

23. Each primary coil has 1,020 turns, and the length of each turn is 23.17 inches. The resistance of each primary coil will then be

$$R_p = \frac{1,020 \times 23.17}{8,234} = 2.87 \text{ ohms}$$

and the resistance of the two coils in series will be 5.74 ohms.

The primary $I^2 R$ loss will therefore be

$$I_p^2 R_p = (4.25)^2 \times 5.74 = 103.7 \text{ watts} \qquad (8)$$

The total I^2R loss in the coils as designed is about 176 watts instead of the 140 watts allowed. The difference, however, is not great enough to make a very large difference in the efficiency. It will be noticed that the loss in the primary coils is rather high, since the loss should be about equally divided between the primary and secondary. This can be remedied to some extent by lowering the primary resistance, i. e., by using a larger wire for the primary winding. We will have room enough to do this because we found that there would be a clearance of $\frac{1}{1}\frac{5}{6}$ inch between the coils. Suppose we try a No. 10 wire for the primary and see if this will give a more satisfactory result. The insulated diameter of this wire will be about .112 inch. The number of turns that can be placed in one layer will be $\frac{17.25}{.112} = 154$. We will therefore use six complete layers with 154 turns each, and one additional layer with 96 turns. The coil at the part where it is wound seven layers deep will have a thickness of $7 \times .112 + 6 \times .020 + \frac{1}{8} = 1.029$ inches.

This will increase the mean diameter slightly and make the mean length of a turn about 23.3 inches. The cross-section of the wire will now be 10,380 circular mils, so that the resistance of each primary coil will be

$$R_p = \frac{1{,}020 \times 23.3}{10{,}380} = 2.29 \text{ ohms}$$

and the resistance of the two coils will be 4.58 ohms.

The loss in the primary at full load will then be

$$I_p^2 R_p = (4.25)^2 \times 4.58 = 83 \text{ watts, nearly}$$

This makes the total I^2R loss $72 + 83 = 155$ watts, instead of 176. This change in the primary winding makes the loss in the primary and secondary more nearly equal, and brings the total loss down nearly to the required amount. We will therefore adopt this winding in place of the one previously calculated. The outside diameter of the primary coils will now be a little over $8\frac{1}{2}$ inches, so that there will still be a clearance of about $\frac{1}{2}$ inch between them

when the transformer is assembled. The total loss at full load will be $110 + 155 + 14 = 279$ watts. The full-load efficiency will then be $\frac{8000}{8279} = .9663$, or about .17 per cent. lower than was assumed when starting out to design the transformer.

EFFICIENCY CURVE

24. The curve showing the relation between the efficiency and output can be readily plotted when the efficiencies at different loads are known. We will therefore calculate the efficiency for one-eighth, one-fourth, one-half, three-fourths, and full load, also for one-fourth overload. In order to do this, we will assume that the core loss remains constant. For example, at one-fourth load the useful output is 2,000 watts, and the secondary current 20 amperes.

TABLE I

Fraction Full Load	Secondary Output Watts	Secondary Current Amperes	Primary Current Amperes (Approx.)	Core Loss	Primary I^2R Loss	Secondary I^2R Loss	Total Loss	Total Input (Approx.)	Efficiency Per Cent.
$\frac{1}{8}$	1,000	10	.60	124	1.65	1.12	126.8	1,127	88.73
$\frac{1}{4}$	2,000	20	1.12	124	5.72	4.48	134.2	2,134	93.72
$\frac{1}{2}$	4,000	40	2.16	124	21.39	17.92	163.3	4,163	96.08
$\frac{3}{4}$	6,000	60	3.20	124	46.9	40.32	211.2	6,211	96.60
Full load	8,000	80	4.25	124	83.00	72.00	279.0	8,279	96.63
$\frac{1}{4}$ overload	10,000	100	5.30	124	128.65	112.00	365.0	10,365	96.48

The primary current will be that corresponding to the secondary current of 20 amperes (or 1 ampere, since the ratio of transformation is 1 to 20) plus the current necessary to set up the magnetization and supply the losses. The primary current at one-fourth load may be taken as approximately 1.12 amperes, since the amount of current required to supply the losses will be very small at this load. The

primary I^2R loss will be $(1.12)^2 \times 4.58 = 5.72$ watts. The secondary I^2R loss will be $(20)^2 \times .0112 = 4.48$ watts. The core loss is 124 watts; hence, the total loss will be 134.2 watts. The input will then be 2,134 watts approximately, and the output 2,000, giving an efficiency at this load of 93.72 per cent. The calculations and results for the other loads are given in Table I.

25. These values of the load and efficiency give the curve shown in Fig. 12. The student should compare this

Efficiency.

Output in fractions of full load.

Efficiency curve for transformer designed.

FIG. 12

curve with that shown in Fig. 1. The scale used for the efficiency in Fig. 12 is larger than that in Fig. 1, in order to show the variation of efficiency more clearly, but it will be noticed that the curves have the same general characteristics. The variation in efficiency in this case is not more than 3 per cent. from one-fourth load to 25 per cent. overload. It will be seen from the table that the efficiency begins to drop off when the transformer is overloaded, owing to the rapid increase of the I^2R losses.

ALL-DAY EFFICIENCY

26. The efficiency that actually determines the cost of operating the transformer is the **all-day efficiency,** or the ratio of the watts useful output per day to the watts supplied during the day. This will depend on the length of time during the day that the transformer is doing useful work. For example, suppose the transformer were worked during the 24 hours an amount equivalent to full load for 6 hours, and that it remained idle an amount of time equivalent to 18 hours. The core losses would go on for the whole 24 hours, because the pressure is maintained across the lines, whether the transformer is working or not. The watt-hours wasted in the form of core losses in 1 day would therefore be $124 \times 24 = 2,976$. The copper losses during 1 day would be equivalent to the sum of the primary and secondary full-load copper losses for 6 hours. Hence, the watt-hours energy wasted in I^2R losses per day will be $155 \times 6 = 930$. The useful energy delivered during the day is equivalent to full load for 6 hours, or $8,000 \times 6 = 48,000$ watt-hours. The energy that must be supplied during the day is $48,000 + 2,976 + 930 = 51,906$ watt-hours, and the all-day efficiency under these conditions is $\frac{48000}{51906} = .925$, nearly. This means that of all the energy delivered to the transformer during 24 hours, 92.5 per cent. is converted into useful energy and the remainder wasted. If the transformer were loaded for a longer period during the day, the useful work done would be greater and the I^2R loss would also be greater. The core loss would remain the same as before, so that the all-day efficiency would depend on the relation between the copper and iron losses. For example, suppose the transformer were fully loaded for 10 hours instead of 6. The useful work would be 80,000 watt-hours and the energy wasted in copper losses 1,550 watt-hours. The core loss would be 2,976, as before, and the total energy supplied would be 84,526, giving an all-day efficiency of about 94.6 per cent. The condition of load for which any given transformer will give its maximum all-day

efficiency depends, therefore, on the relation between the copper and iron losses. It also follows that if the transformer is to be loaded for only a short period during the day, the iron losses should be small if the all-day efficiency is to be high.

MAGNETIZING CURRENT

27. The current that the primary of a transformer takes from the line when its secondary is an open circuit is usually spoken of as the **magnetizing current,** although, strictly speaking, it is the resultant of the magnetizing current proper and the current that represents the energy necessary to supply the core losses. It is important that this no-load current should be small, because if a large number of transformers are connected to the line, the sum of all the magnetizing currents required by the separate transformers may represent a considerable current to be supplied from the station. This means that the alternator may be delivering a fairly large current when no useful work is being done. It is true that this current may not represent very much power, because it is considerably out of phase with the E. M. F., but it loads up the lines and alternator, and thus limits their useful current-carrying capacity. The no-load current is made up of two components, one of which is the magnetizing current, or the current that sets up the ampere-turns necessary to drive the flux around the core. The other component represents that current which is necessary to supply the core losses, and is in phase with the impressed E. M. F. The core loss in this case is 124 watts; hence, this component of the no-load current will be $\frac{124}{2000}$ = .062 ampere.

28. The component of the no-load current that represents the current necessary to set up the magnetic flux may be obtained as follows: For a magnetic density of 30,000 lines per square inch, we will require about 5.5 ampere-turns per inch length of the circuit for a good quality of transformer

iron. The mean path for the magnetic flux is shown by the dotted line, Fig. 9; the length of this circuit is about 60 inches. The ampere-turns required to set up the flux will then be $60 \times 5.5 = 330$. The number of primary turns surrounding the circuit is 2,040. We then have magnetizing current $\times$ 2,040 = 330, or current = .162 ampere.

The no-load current is therefore made up of the two components .062 and .162 at right angles to each other, and its value is $I_m = \sqrt{.062^2 + .162^2} = .17$ ampere.

This is the current that the transformer will take from the line when it is operating under no load. This does not mean, however, that it is consuming $.17 \times 2{,}000$, or 340 watts, because the no-load current is always considerably out of phase with the E. M. F., and, as a matter of fact, the transformer consumes only sufficient power to make up for the core losses and the slight loss in the primary due to the no-load current. At no load, the power factor may be considerably less than 1, but as the load is increased, the current and E. M. F. shift into phase until the power factor at full load is very nearly unity.

REGULATION

29. As the secondary voltage will fall off as the load is applied, it is important that this falling off should be slight. In well-designed transformers the falling off in secondary voltage may vary from 1 to 2.5 or 3 per cent., depending on the output. This drop is due to magnetic leakage and the resistance of the primary and secondary coils. In the type of transformer designed, the falling off due to magnetic leakage will be quite small, because the coils are wound one over the other, making the path between the coils, through which leakage is set up, long and of small cross-section. The leakage drop would not likely amount to more than .2 or .3 volt. The drop in the secondary coils at full load will be current $\times$ resistance $= 80 \times .0112 = .89$ volt. The drop in the primary at full load due to

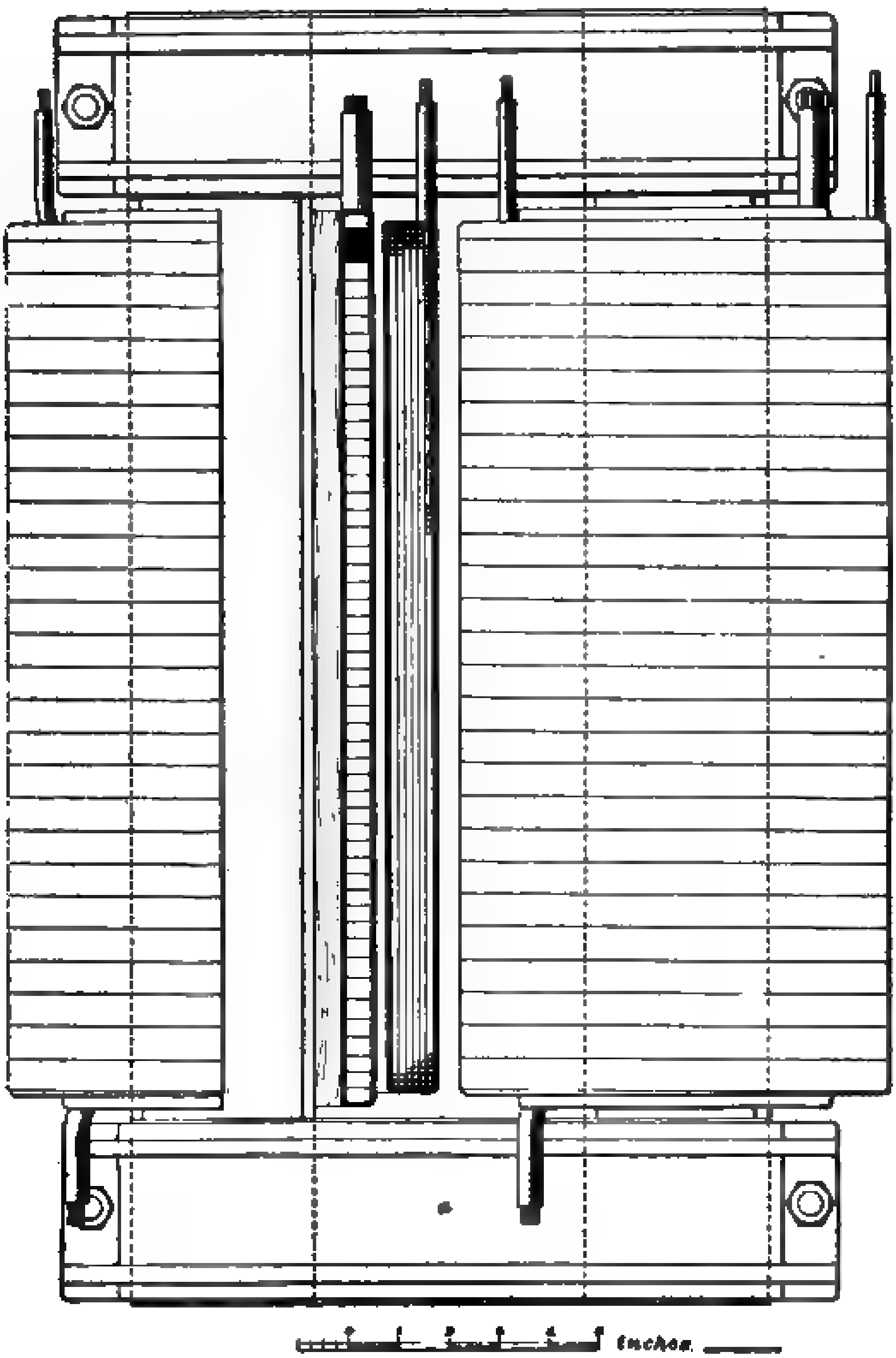


FIG. 18

the primary resistance will be $4.25 \times 4.58 = 19.46$ volts. This drop of 19.46 volts in the primary will cause a corresponding drop of $\frac{19.46}{20} = .97$ volt in the secondary. The total drop due to leakage and resistance combined will therefore be under 2 volts, or 2 per cent. of the output, which is close enough regulation for all practical purposes.

CONSTRUCTION

30. The **construction and arrangement** of the core and coils will be understood by referring to Fig. 13. This shows an elevation of the assembled transformer, with a longitudinal section of the coils showing the windings and insulation. The core is built up out of thin iron strips, which are interleaved at the corners, so as to practically do away with joints in the magnetic circuit. The plates are shown held in position by clamps *a*, drawn up by bolts *b*. The terminals of the coils should be very heavily insulated, and may be run to a connection board within the transformer, or taken directly out through the case. Transformers in sizes up to 20 or 30 kilowatts are usually placed in an iron case arranged for mounting on poles. These cases should be weather-proof, and made as light as possible consistent with the necessary strength. They are generally designed with a view to being filled with oil. Fig. 14 shows a case suitable for the transformer designed. This is made of cast iron about $\frac{5}{16}$ or $\frac{1}{4}$ inch thick. The case *a* is provided with a cover *b*, which is bolted on by means of the bolts *d*. The overlapping flange and gasket *c* serve to make the cover water-tight. The transformer, which is shown by the dotted outline, is held in place by setscrews. The primary terminals are brought out through the bushings *e*, and four bushings *f* are provided on the front of the case for the secondary terminals. The bushings should be of heavy hard rubber or porcelain, and so constructed that they will prevent leakage of current from the lines to the case.

These outlets should, of course, be directed downwards, so that the wires may be looped into them, thus preventing water from getting into the case. Lugs *g*, *g* should be provided on the back of the case for attaching suspension hooks. Fuses are usually provided between the primary and the

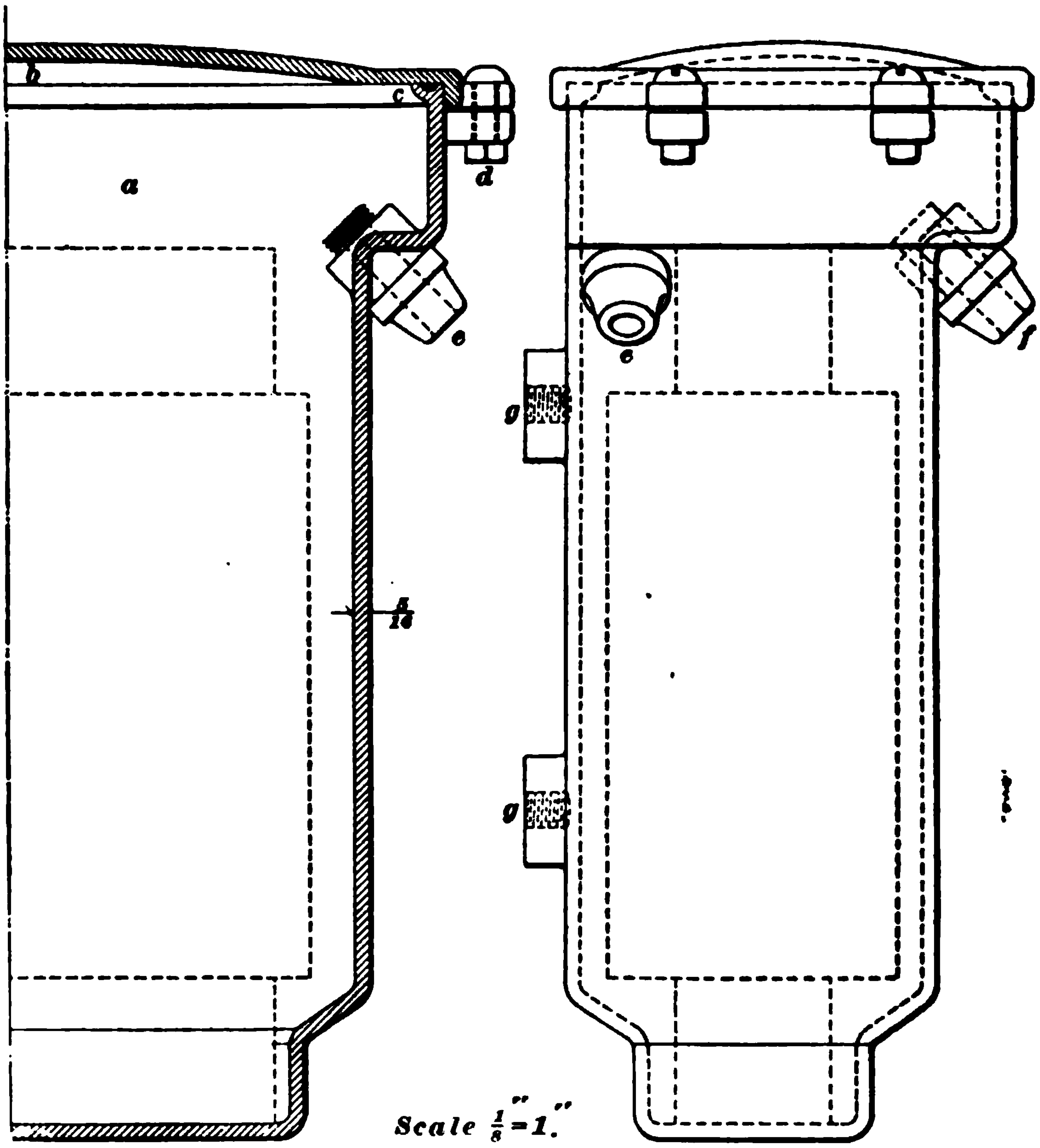


FIG. 14

line, but these are generally mounted outside the transformer case in separate fuse boxes of special construction. Secondary fuses are not provided at the transformer, the fuses in connection with the secondary service wires being depended on to protect the secondary circuit. For large indoor transformers, only sufficient covering is used to

protect the coils, a regular case being unnecessary, as well as interfering with the ventilation.

31. The transformer that has been worked out is one that would be used on an ordinary lighting circuit. The method of designing a step-up transformer would be essentially the same, except that extra precautions would be taken to insure very high insulation, and a larger allowance of winding space would be necessary. The design of a shell transformer may be also carried out in about the same way. The core proportions shown in Fig. 15 may be taken as a

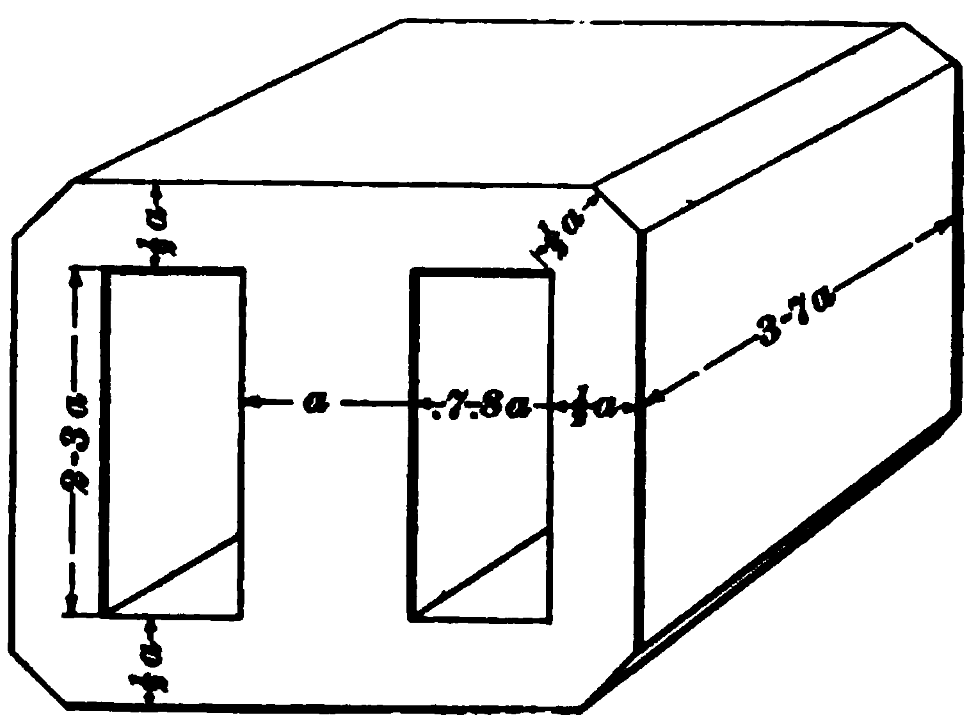


Fig. 15

starting point. All dimensions are referred to the width of the tongue a, which carries the lines through the coils. The length of the core may be from 3 to 7 times a. The height of the winding space is usually from 2 to 3 times a, and the breadth from .7 to .8 times a. The thickness of the outer part of the shell around the coils is necessarily one-half of a, because this part of the core carries one-half the flux passing through the coils. In this type of transformer the allowance of copper will usually be somewhat less than in the core type, because the winding space is more restricted.

INDUCTION MOTORS

32. In many respects the action of an **induction motor** resembles that of a transformer, and, consequently, parts of its design can be carried out by methods similar to those used in designing transformers. The primary of the induction motor, that is, the part into which currents are led from the line, corresponds to the primary coil of the transformer, while the secondary, or the part in which the currents are induced, corresponds to the secondary. This relation holds, whether the primary or secondary is the revolving part; but in all that follows we will consider the primary as being fixed and the secondary as revolving. In such an arrangement, the fixed primary is commonly spoken of as the **field,** or **stator,** and the secondary as the **armature,** or **rotor.** The essential difference between an induction motor and a transformer is that in the latter case the secondary core and windings are fixed as regards the primary, and the E. M. F. generated in the secondary is made use of to supply useful electrical energy to an outside circuit; while in the former case the secondary core and windings revolve with regard to the primary, and the mechanical torque action between the primary and secondary is made use of to deliver mechanical energy. The currents generated in the secondary are not led into an outside circuit, but flow within the secondary itself, in order that they may react on the field produced by the primary and so cause the armature or secondary to exert the required effort at the pulley. A transformer supplied with a constant primary pressure will furnish a nearly constant secondary pressure independently of the load; an induction motor when supplied with a constant primary pressure will run at nearly constant speed independently of the load.

LIMITATION OF OUTPUT

33. The **output of induction motors,** like that of alternators and transformers, is limited principally by the heating effect due to the various losses that occur in the motor when it is loaded. The principal loss is that due to the resistance of the primary and secondary conductors, although the hysteresis and eddy-current losses may also be considerable if the motor is not properly designed. If an induction motor is considerably overloaded, the armature currents react excessively on the field, causing excessive magnetic leakage along the air gap, and greatly lessening the torque between the field and armature. If the overload is sufficiently great, the torque will be reduced to such an extent that the motor will stop. Usually, however, an induction motor may be loaded for short periods beyond its full-load capacity without danger of overheating or stopping.

PRIMARY CORE LOSSES, MAGNETIC DENSITIES, ETC.

34. The losses in the primary are made up of the core loss due to hysteresis and eddy currents, and the copper loss due to the resistance of the primary winding. The frequency of the changes in the magnetism of the primary is the same as the frequency of the current magnetizing it; hence, the lower the frequency at which the motor is operated, the higher is the allowable value of the magnetic density in the primary core. The core densities used for such motors should be about the same as those used for transformers operating at the same frequency. The curve, Fig. 16, shows the relation between the maximum value of the density and the frequency, based on values given by Kolben. The densities are low, and lie between 40,000 and 20,000 lines per square inch throughout the range of frequencies commonly met with in practice. This curve gives the density in the core proper; the density in the teeth of the primary and secondary may be double these values

without making the hysteresis loss very large, the volume of the teeth being small. Motors are also commonly built in which the magnetic density will be found less than that given by the curve, but the values shown should not, as a rule, be exceeded. Induction motors, like alternators, are generally built with several poles, so that the magnetic flux is subdivided. The required cross-section of iron in the yoke is therefore small, and a low magnetic density may be used without making the machine very heavy. The eddy-current loss in the primary, like that in transformer cores, can be kept down to a very small amount if thin disks are used. The thickness of stampings used is about the same as for alternator armature cores, namely, from .012 inch to .018 inch.

Maximum magnetic density (lines per sq in.)

Magnetic densities for Induction Motors

FIG. 16

SECONDARY CORE LOSSES, MAGNETIC DENSITIES, ETC.

35. The core losses in the secondary are usually quite small. This is due to the fact that the frequency of the reversals of magnetism in the secondary is low. If the armature were standing still, the slip between primary and secondary would be 100 per cent., and the frequency of the magnetic cycles in the secondary would be the same as in

the primary. When, however, the motor is running under normal conditions, the slip may not be more than from 2 to 5 per cent. The frequency of the magnetic cycles in the armature will therefore be only from 2 to 5 per cent. of the frequency in the field, and the core losses will be correspondingly small.

INDUCTION-MOTOR WINDINGS

PRIMARY WINDING

36. The winding on the primary must be so designed that it will generate a counter E. M. F. equal and opposite to that of the mains, neglecting the small drop due to the resistance of the coils. It is therefore determined in a manner similar to that used for the calculation of the primary winding for a transformer. In some of the earlier forms of induction motors the coils were wound on salient poles, but in modern machines they are placed in slots in the same way as windings for alternator armatures. Most induction motors are of the two-phase or three-phase type, and the field winding of such machines is carried out in the same way as the winding for the armature of a two-phase or three-phase alternator. The primary winding may be concentrated or distributed, the latter arrangement being most generally used for machines operating at moderate pressures. We may write for induction-motor windings

$$E = \frac{4.44\,\Phi\,T\,n}{10^8} \times k \qquad \textbf{(9)}$$

as explained in connection with alternator windings. In this formula

E = E. M. F. generated by or impressed on each phase;
T = number of turns connected in series per phase;
Φ = maximum total magnetic flux from one pole;
n = frequency (cycles per second);
k = a constant depending on the style of winding used.

For a concentrated winding, that is, one with one group of conductors per pole per phase, $k = 1$. For a uniformly distributed two-phase winding, $k = .90$. For a uniformly distributed three-phase winding, $k = .95$. If the winding is only partially distributed, the value of k will lie between the values just given and 1. It will be noticed that for a given value of the flux, frequency, and number of volts applied, the number of turns required for a distributed winding is but slightly more than that required for a concentrated winding, the difference being about 10 per cent. for a two-phase motor and 5 per cent. for a three-phase. The distributed windings are preferred, because with them there is less magnetic leakage between the primary and secondary; this decreases the inductance and improves the power factor of the motor. Generally, the primary slots occupy about one-half the circumference of the primary core, as this arrangement allows a fair amount of space for the windings without forcing the density in the teeth too high.

37. The cross-section of the conductor used for the primary winding is determined by the full-load current that the motor takes in each phase. The relation of this current to the full-load current taken from the mains will, of course, depend on the way in which the different phases are connected up. The primary is usually stationary, and cannot therefore radiate its heat as readily as if it were revolving. For this reason, the current density should be kept as low as possible without making the space occupied by the windings too large. Induction-motor fields usually present quite a large radiating surface, and are, moreover, generally supplied with air ducts, through which a draft is caused by the armature. If it were not for this, the allowance per ampere would have to be considerably more. The circular mils allowed per ampere varies greatly in different makes of machines. In some it may be as low as 500 or 600, and in others it may be 1,100 or 1,200. Much depends on the way in which the machine is ventilated, but it is always best to

make the allowance as large as possible without interfering with the design in other respects.

38. The primary winding may be made up of bars or coils, depending on the voltage at which the machine is to operate, coils being used on most machines of moderate size. These are arranged in the same way as has already been described for two-phase and three-phase armatures, and what has been said as regards the insulation, etc. of such armatures applies also to induction-motor primaries. The primary winding is very often arranged in two layers, form-wound coils being used.

SECONDARY WINDING

39. The number of conductors used for the **secondary winding** is largely a matter of choice. The motor may be built with any ratio of transformation, that is, with any ratio of primary to secondary conductors, and work well. It is desirable, however, to make the resistance of the secondary low, and to get as large a cross-section of copper as possible into the slots. For this reason, it is usual to provide the secondary with only one or two bars to each slot, the space taken up by insulation being thus reduced to a minimum. The bars are generally rectangular in section, though in some machines round bars have been used.

40. The secondary conductors are in many cases grouped into a regular two-phase or three-phase bar winding. It is necessary to use a wound secondary of this kind when it is desired to insert resistance in series with the secondary, either for the purpose of securing a good starting torque or regulating the speed. When this is done, the

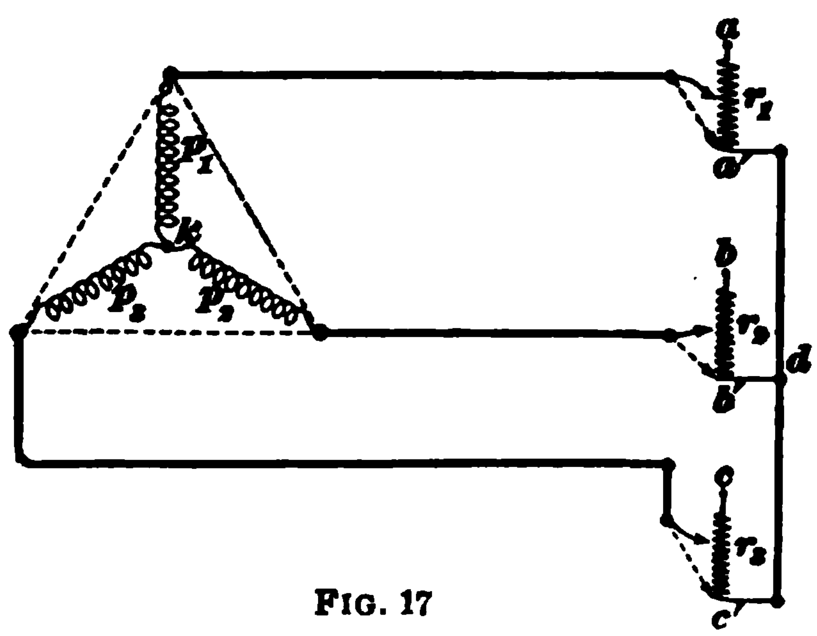


FIG. 17

winding is connected up according to the Y method, and the three terminals brought to collector rings, as shown in Fig. 17. The three phases p_1, p_2, and p_3 are thus connected to the three resistances r_1, r_2, and r_3, as shown. When the motor is being started, the phases are connected to the points *a*, *b*, and *c*, and the resistance is gradually cut out as the motor runs up to speed.

41. When it is not desired to insert resistance in the secondary circuit, a plain squirrel-cage winding may be used. There is in this case only one bar in each slot, all of them being connected by copper short-circuiting rings at each end of the armature. The squirrel-cage construction gives a durable and efficient armature, because the winding is extremely simple, and the end connections between the bars are of very low resistance. Since the voltage generated in an induction-motor secondary is very low, the insulation between the bars and core need not be heavy, as the danger of burn-outs is almost nil and short circuits do not count for much, because the bars are short-circuited by the end connecting rings. Usually, the number of slots in the secondary is different from the number in the primary, though this is not absolutely necessary. The use of a different number of slots tends to avoid any dead points at starting, and prevents the motor from acting merely as a static transformer with a short-circuited secondary.

POWER FACTOR

42. It is important that the **power factor** of an induction motor be high, otherwise it will take an excessive amount of current for a given amount of power delivered, on account of the angle of lag between the current and E. M. F. In order that the power factor may be high when the motor is loaded, the magnetic leakage and consequent inductance must be kept low. This may be done by using a small air gap, subdivided windings, and slots that are partially opened at the top.

LENGTH OF AIR GAP

43. The current necessary to set up the magnetic flux through the field will be largely dependent on the **length of air gap** between the primary and secondary, because this constitutes by far the greater part of the reluctance of the magnetic circuit. In a transformer it is not necessary to have any air gap in the magnetic circuit; hence, the magnetizing current can be made quite small. In an induction motor, however, an air gap is unavoidable, and all that can be done is to reduce this to the smallest possible amount. The air gap is therefore made as small as the necessary mechanical clearance will permit. For very small motors the single air gap may not be more than $\frac{1}{100}$ inch. For larger machines it must be greater than this, on account of the difficulty of centering large armatures exactly, and to prevent the armature touching the field in case the bearings should wear slightly.

GENERAL DATA

44. The following figures, given by M. A. C. Eborall,* will serve as a guide for the values of some of the various items entering into the design of induction motors. These apply for the most part to motors designed for the ordinary frequencies of 50 to 60 cycles. These must be taken as a general guide only, and individual machines might show values differing considerably in some particulars from these and yet give good results.

45. Peripheral Speeds.—From 4,000 to 7,000 feet per minute. The speed of large motors is usually somewhat higher than that of the smaller machines.

46. Number of Poles.—Two to $7\frac{1}{2}$ horsepower, 4 poles; 10 to 30 horsepower, 6 poles; 40 to 100 horsepower, 8 poles.

47. Full-Load Efficiency.—Table II gives ordinary values for the full-load efficiency.

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* *London Electrician*, 1900.

TABLE II

Brake Horsepower	2	5	10	25	50
Polyphase motors.......	.75	.79	.85	.87	.90
Single-phase motors.....	.72	.75	.80	.83	.85

48. Full-Load Power Factor.—Table III gives ordinary values for the full-load power factor.

TABLE III

Brake Horsepower	2	5	10	25	50
Polyphase motors.......	.78	.80	.85	.87	.88
Single-phase motors.....	.72	.75	.80	.83	.85

49. Length of Air Gap.—The following values (Table IV) give the minimum length of air gap that it is safe to use for mechanical reasons. In some machines larger air gaps than these are employed. The lengths given refer to a single gap only.

TABLE IV

Rotor Diameter	Air-Gap Length Inch
Between 5 inches and 8 inches............	$\frac{1}{100}$
Between 9 inches and 12 inches............	$\frac{1}{75}$
Between 15 inches and 20 inches............	$\frac{1}{32}$
Between 24 inches and 32 inches............	$\frac{1}{16}$
Between 40 inches and 60 inches............	$\frac{1}{8}$

50. Density of Magnetism in Stator Teeth.—Table V gives values for the density in the stator teeth.

TABLE V

Horsepower	Density in Lines Per Square Inch
2 to 7.5	65,000
10 to 30	70,000
40 to 100	80,000
Above 100	85,000

The density in the air gap should not exceed 30,000 lines per square inch, and is usually considerably lower than this.

51. Density of Magnetism in Rotor Teeth.—Table VI gives values for the density in the rotor teeth.

TABLE VI

Horsepower	Density in Lines Per Square Inch
2 to 7.5	80,000
10 to 30	85,000
40 to 100	90,000
Above 100	100,000

52. Current Densities per Square Inch.—With low and medium pressure semi-enclosed motors, the amperes per square inch cross-section of stator or field conductor will be between 1,500 and 1,100, according to size. This corresponds approximately to 850 to 1,150 circular mils per ampere. With high-tension motors, somewhat smaller values must be taken on account of the space occupied by the insulation.

53. Volume of Current in Stator and Rotor.—The ampere-conductors, i. e., the product of the current and

conductors, for each inch periphery should have values about as shown in Table VII.

TABLE VII

Horsepower	Ampere-Conductors Per Inch of Periphery
2 to 7.5	250
10 to 30	330
40 to 100	430
100 to 150	570
Above 200	600

54. Slip at Full Load.—Table VIII gives approximate values of the slip at full load in per cent. of synchronous speed.

TABLE VIII

Horsepower	Slip Per Cent.
2 to 5	7
7½ to 15	5
20 to 40	4
50 to 100	3

DESIGN OF 10-HORSEPOWER MOTOR

55. In order to illustrate the design of a simple induction motor, we will take an example and make the calculations required for the windings and core. Many of the mechanical details are similar to those that have already been described for alternators, so that they need not be taken up in detail; those parts that differ materially will be described as the design is worked out. We will take for an example a 10-horsepower three-phase motor with stationary primary and revolving secondary. The primary will be

provided with a distributed winding placed in slots, the secondary being provided with a squirrel-cage winding. We will suppose that the following quantities are given: Output at pulley, 10 horsepower; line voltage, 220 volts; frequency, 60 cycles per second; power factor at full load, .85; commercial efficiency at full load, 85 per cent.

FULL-LOAD CURRENT IN PRIMARY

56. The output is to be 10 horsepower, or $10 \times 746 = 7{,}460$ watts $= W$. The actual power to be delivered to the motor at full load will therefore be $\frac{7{,}460}{.85} = 8{,}776$ watts $= W'$.

The true watts delivered to the motor at full load are equal to the product of the volts and amperes into the power factor $\cos \phi$, where ϕ is the angle of lag between the current and E. M. F. We then have

$$\text{apparent watts} = \frac{\text{true watts}}{\cos \phi} \qquad \textbf{(10)}$$

$\cos \phi = .85$ in this case; hence, we have

$$\text{apparent watts} = \frac{8{,}776}{.85} = 10{,}324 = W''$$

For a three-phase motor we have

$$W'' = E I \sqrt{3}$$

where E is the voltage between the lines, and I the current in each line; hence,

$$10{,}324 = 220 \times I \times \sqrt{3}$$

$$I = \frac{10{,}324}{220 \times \sqrt{3}} = 27.1$$

The full-load current in the line will therefore be 27.1 amperes, and the current in each phase will also be 27.1 amperes if we adopt a Y winding for the primary. If we used a Δ winding, the current in each phase would be $\frac{27.1}{\sqrt{3}} = 15.7$ amperes, nearly.

SIZE OF PRIMARY CONDUCTOR

57. Since the current in each phase is comparatively small, we will use the **Y** method of connection for the primary winding. The current in the primary conductor will therefore be 27.1 amperes. We will provide 850 circular mils per ampere as a fair allowance of copper for the primary. We then have $27.1 \times 850 = 23{,}035$ circular mils.

A No. 6 B. & S. has a cross-section of 26,251 circular mils, and three No. 11 wires in multiple give a cross-section of 24,702 circular mils. Two No. 9 wires in parallel will give 26,188 circular mils, so that any of these arrangements would give the requisite cross-section. When it comes to arranging the dimensions of the slot, a decision can be made as to which arrangement can be used to best advantage.

PERIPHERAL SPEED AND DIAMETER OF ARMATURE

58. If the speed of rotation and the frequency are fixed, the number of poles for which the field must be wound is at once determined; or, if the number of poles and frequency be fixed, the speed of rotation at no load at once follows, because at no load the speed of the armature is almost exactly equal to that of the revolving field, the slip being very small. If we wind the field so as to have six poles, the speed at no load will be very nearly $s = \frac{2 \text{ frequency}}{\text{number of poles}}$ $= \frac{2 \times 60}{6} = 20$ revolutions per second, or 1,200 revolutions per minute. If the field were wound for eight poles, the speed would be 900 revolutions per minute. As this motor is not very large, 1,200 revolutions per minute will be a fair speed for it. If we used the eight-pole arrangement, we would obtain a lower speed, but the motor would be larger and more expensive; we will therefore adopt the six-pole 1,200-revolution arrangement.

59. Induction motors are run at moderately high peripheral speeds, usually between 4,000 and 7,000 feet per minute, the larger motors having the higher peripheral speed. For a motor of the size under consideration, 4,500 feet per minute will be a fair value. The outside diameter of the armature will therefore be

$$d_a = \frac{\text{peripheral speed} \times 12}{\text{R. P. M.} \times \pi} = \frac{4{,}500 \times 12}{1{,}200 \times \pi} = 14.324 \text{ inches}$$

We will therefore adopt $14\frac{3}{8}$ inches as the outside diameter of the armature. The circumference of the armature will be about 45.16 inches. The inside diameter of the field will be equal to the outside diameter of the armature plus the air gap required for mechanical clearance. For an armature of this diameter $\frac{1}{32}$ inch on each side should be sufficient, so that the inside diameter of the field will be $14\frac{3}{8} + 2 \times \frac{1}{32} = 14\frac{7}{16}$ inches. The inside circumference of the field will be about 45.35 inches.

PRIMARY WINDING

60. We will use a **primary winding** that is subdivided. If the winding is subdivided to a large extent, a large number of slots will be required to accommodate it. It is usually sufficient, however, for motors ranging from 10 to 100 horsepower, to use from two to four coils per pole per phase, and for the present case we will take three coils per pole per phase as a trial arrangement. The winding will be arranged in two layers; hence, there will be as many slots as coils. The number of slots will therefore be $3 \times 6 \times 3 = 54$.

61. Before fixing upon the size of the slots, it will be necessary to determine the number of conductors. We will design the primary so as to make the ampere-conductors per inch of periphery as nearly 300 as possible, as this should give good results for a motor of this size. The circumference of the stator is $14\frac{7}{16} \times 3.1416 = 45.35$ inches; hence,

the total ampere-conductors will be $45.35 \times 300 = 13{,}605$. The current in each conductor is 27.1 amperes; hence, number of conductors should be $\frac{13{,}605}{27.1} = 502$, approximately. There are 54 slots, and as the winding is to be arranged in two layers, there must be an even number of conductors per slot, so that the nearest number will be 10. This will make the nearest total number of conductors 540.

62. In order to obtain a slot that will be fairly deep compared with its width, we will use three No. 11 wires in

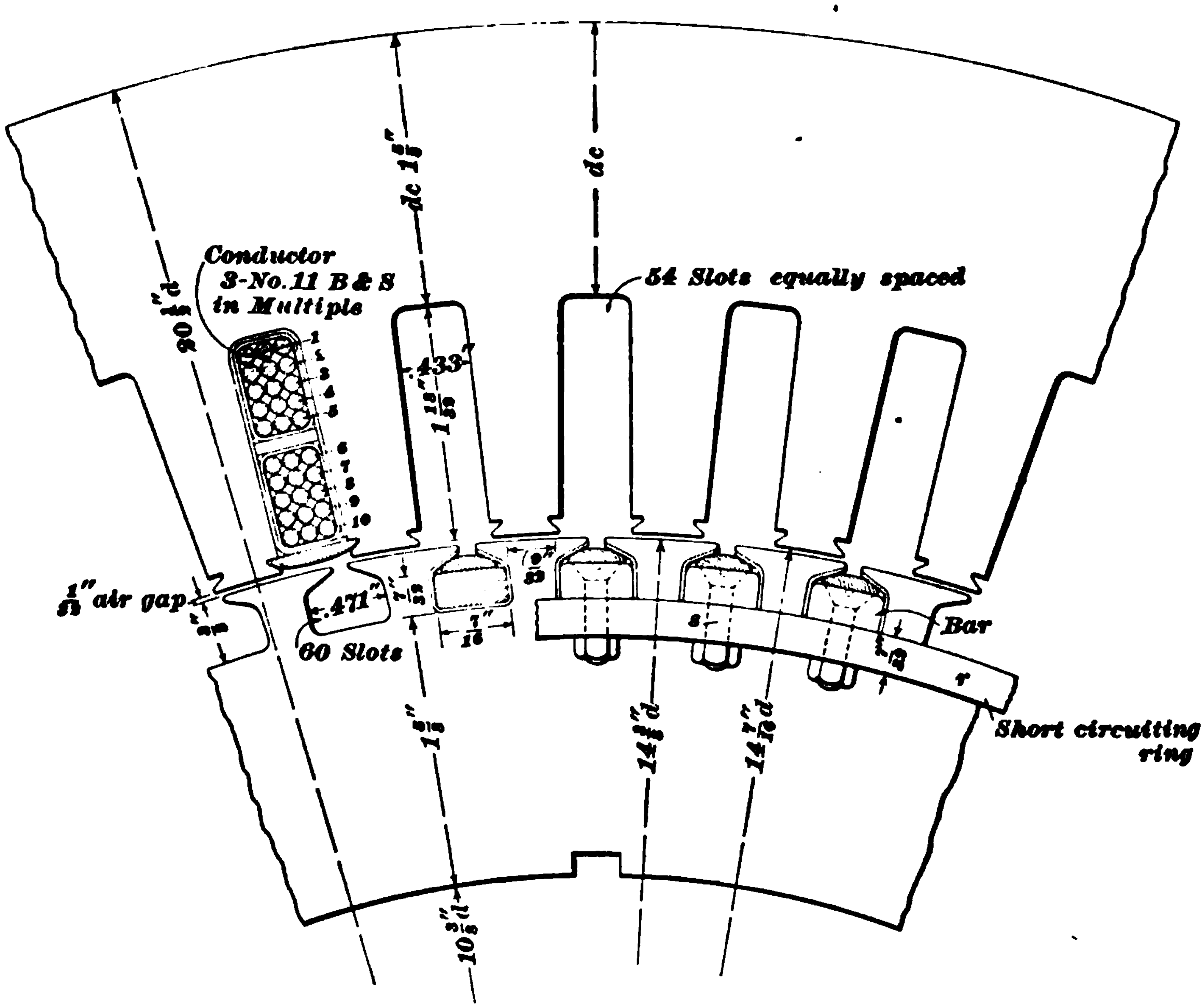


FIG. 18

multiple, with a cotton wrapping on each wire. The diameter of the wire over the insulation will be .101 inch, and

allowing 65 mils on each side for slot insulation, taping, and clearance, the width of the slot will be $3 \times .101 + 2 \times .065 = .433$ inch. The space taken up by the 54 slots will be $54 \times .433 = 23.38$ inches, thus leaving $45.35 - 23.38 = 21.97$ inches for the teeth. Each tooth will therefore be $\frac{21.97}{54} = .407$ inch wide at the circumference. This is not much less than the width of the slot, and will give ample cross-section of iron to carry the flux, because the density in the tooth will not be much more than twice that in the air gap, and as the latter will not be more than 20,000 to 25,000 lines per square inch, there will be no danger of the teeth becoming saturated.

The slot must have sufficient depth to accommodate 10 wires in addition to the slot insulation, the dividing insulation between the upper and lower layers of coils, and the wedge or fiber strip used to hold the coils in place. We will allow $\frac{3}{32}$ inch for the middle insulation, and $\frac{5}{32}$ inch for the holding in strip. The total depth of the slot will then be $10 \times .101 + 2 \times .065 + \frac{3}{32} + \frac{5}{32} = 1.390$, or, say, $1\frac{13}{32}$ inches, in order to allow a small amount for clearance. The dimensions of the slot and the arrangement of the ten turns of three-wire conductor are shown in Fig. 18, the coils being held in place by wooden or fiber strips slipped into notches in the teeth.

MAGNETIC FLUX IN POLES

63. By the **magnetic flux** Φ is meant the total maximum number of lines that flow from one pole piece. The pole pieces of an induction motor are not sharply defined like those of an alternator field, but gradually merge from one into the other.

Fig. 19 will help to convey an idea as to the way in which the flux is distributed around the face of an induction-motor field. The inner circle represents the face of the field, which for the present will be considered as unbroken by slots. If a current is sent through the windings, six poles

will be formed, as shown, and these poles will be continually shifting around the ring. We will consider the instant when the centers of the poles are at the points marked N, S. The magnetic density is greatest opposite the center of the pole, and may be represented by the arrow $a\ b$ directed outwards from a south pole, or $a'\ b'$ directed inwards from a north pole. As we move away from a pole the field intensity diminishes until it becomes zero at the point midway between the poles, and begins to increase again in the opposite direction. This variation in the magnetic density at the various points of the pole face is represented approximately by a sine curve, and if the line $a\ b$ represents the maximum value of the density, the average value of the density will be $a\,b \times \frac{2}{\pi}$, since the average value = maximum value $\times \frac{2}{\pi}$. Hence, if **B** represents the maximum value of the density, $\mathbf{B} \times \frac{2}{\pi}$ will be the average density. The total flux Φ is equal to the area of the pole face multiplied by the average value of the density; or

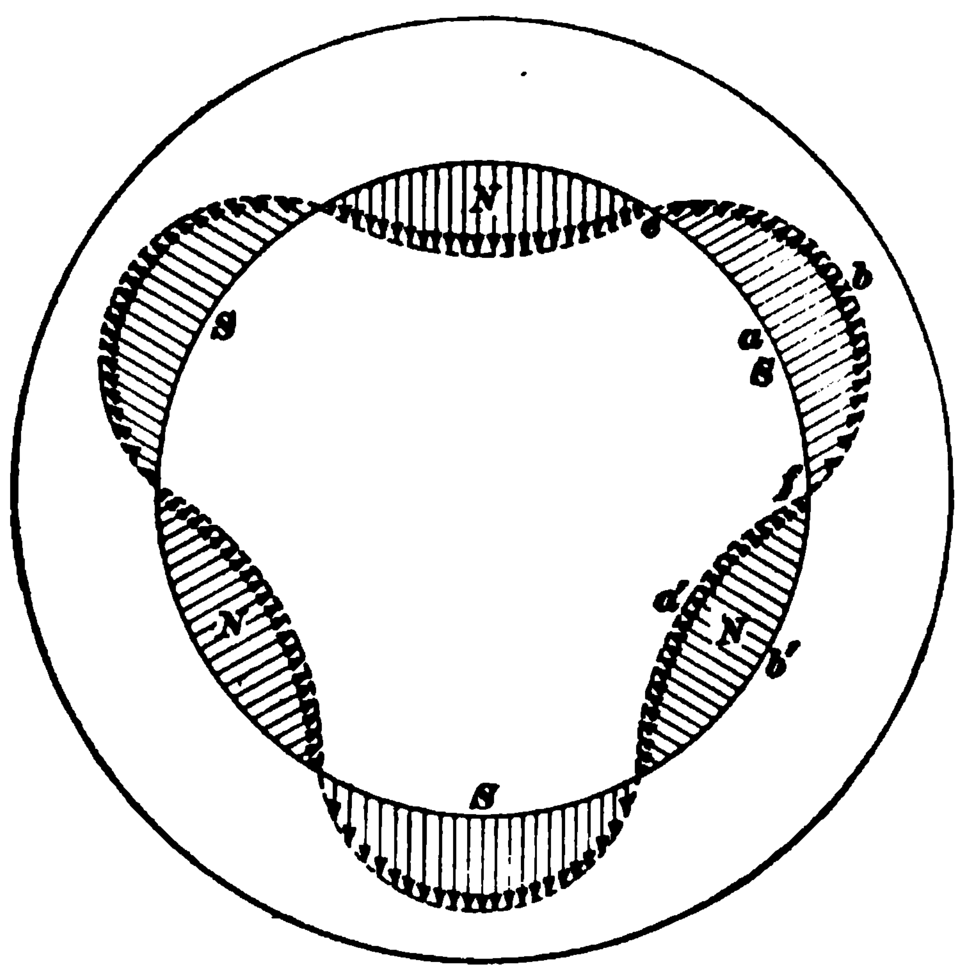


Fig. 19

$$\Phi = \text{arc } ef \times \text{length of field parallel to shaft} \times \mathbf{B} \times \frac{2}{\pi}$$

$$\text{Arc } ef = \frac{\pi \times \text{diameter of field}}{\text{number of poles}}$$

hence, $\Phi = \dfrac{\pi \times \text{diameter of field}}{\text{number of poles}} \times \text{length of field} \times \mathbf{B} \times \dfrac{2}{\pi}$;

or we may write, for the length of field parallel to the shaft,

$$l = \frac{\Phi \times p}{2 \times d_f \times \mathbf{B}} \qquad \textbf{(11)}$$

where Φ = flux from one pole;
p = number of poles;
d_f = inside diameter of field;
$\mathbf{B}$ = magnetic density in the air gap (maximum).

Hence, from this formula we can obtain the length of the field parallel to the shaft when we know the value of Φ and have decided on the air-gap density to be used. The other quantities in the equation are already known. We can obtain the value of the flux from the formula

$$E = \frac{4.44\ \Phi\ T n}{10^8} \times k$$

We will take $k = .95$, as the winding is nearly uniformly distributed. There are eighteen coils in each phase, with 5 turns each, so that the number of turns T in series per phase is 90. The voltage generated in each phase will be, neglecting the resistance drop, $\frac{220}{\sqrt{3}} = 127$ volts, because the armature is **Y** connected. We then have

$$127 = \frac{4.44 \times \Phi \times 90 \times 60 \times .95}{10^8}$$

or $\Phi = \frac{127 \times 10^8}{4.44 \times 90 \times 60 \times .95} = 557,500$ lines, approximately

64. The magnetic density in the air gap should not be forced too high, or a large magnetizing current will be required to set up the flux. From 20,000 to 30,000 lines per square inch may be taken as fair values for the air-gap density. The density at the top of the teeth would of course be more than this. We will take 20,000 lines per square inch in this case. Applying formula **11,** we have for the length of the core parallel to the shaft, the field diameter being $14\frac{7}{16} = \frac{231}{16}$ inch,

$$l = \frac{557{,}500 \times 6 \times 16}{2 \times 231 \times 20{,}000} = 5.79 \text{ inches}$$

The length of the iron part parallel to the shaft should therefore be, say, $5\frac{13}{16}$ inches, in order that the air-gap density shall not exceed 20,000 lines per square inch. The length of core over all will be somewhat greater than this, owing to the space taken up by insulation between the disks and by the air ducts if the latter are used. We will allow $\frac{3}{8}$ inch for an air duct in the center of the core, and $\frac{1}{2}$ inch for the space taken up by the insulation, thus making the spread of the laminations over all $6\frac{11}{16}$ inches.

65. All the dimensions of the primary have now been determined except the depth of the iron under the slots, that is, the dimension d_c, Fig. 18. This must be made such that there shall be a sufficient cross-section of iron to keep the magnetic density down to the proper amount. Referring to the curve, Fig. 16, we find that a fair value for the magnetic density in the iron of a 60-cycle motor is about 30,000 lines per square inch. The magnetic leakage in such a motor is small, and we may take the flux in the field as practically the same as that in the air gap. The flux through a cross-section of the yoke under the slots will be $\frac{1}{2}\,\Phi$, because the flux from one pole will divide, one half flowing in one direction and the other half in the other direction. The area of cross-section of iron in the yoke will therefore be

$$A_y = \frac{\frac{1}{2}\,\Phi}{\mathbf{B}_y}$$

which gives

$$A_y = \frac{278{,}750}{30{,}000} = 9.29 \text{ square inches}$$

The actual length of iron parallel to the shaft is $5\frac{13}{16}$ inches; hence, the depth of iron under the slots must be

$$d_c = \frac{9.29}{5.8125} = 1.6 \text{ inches, nearly}$$

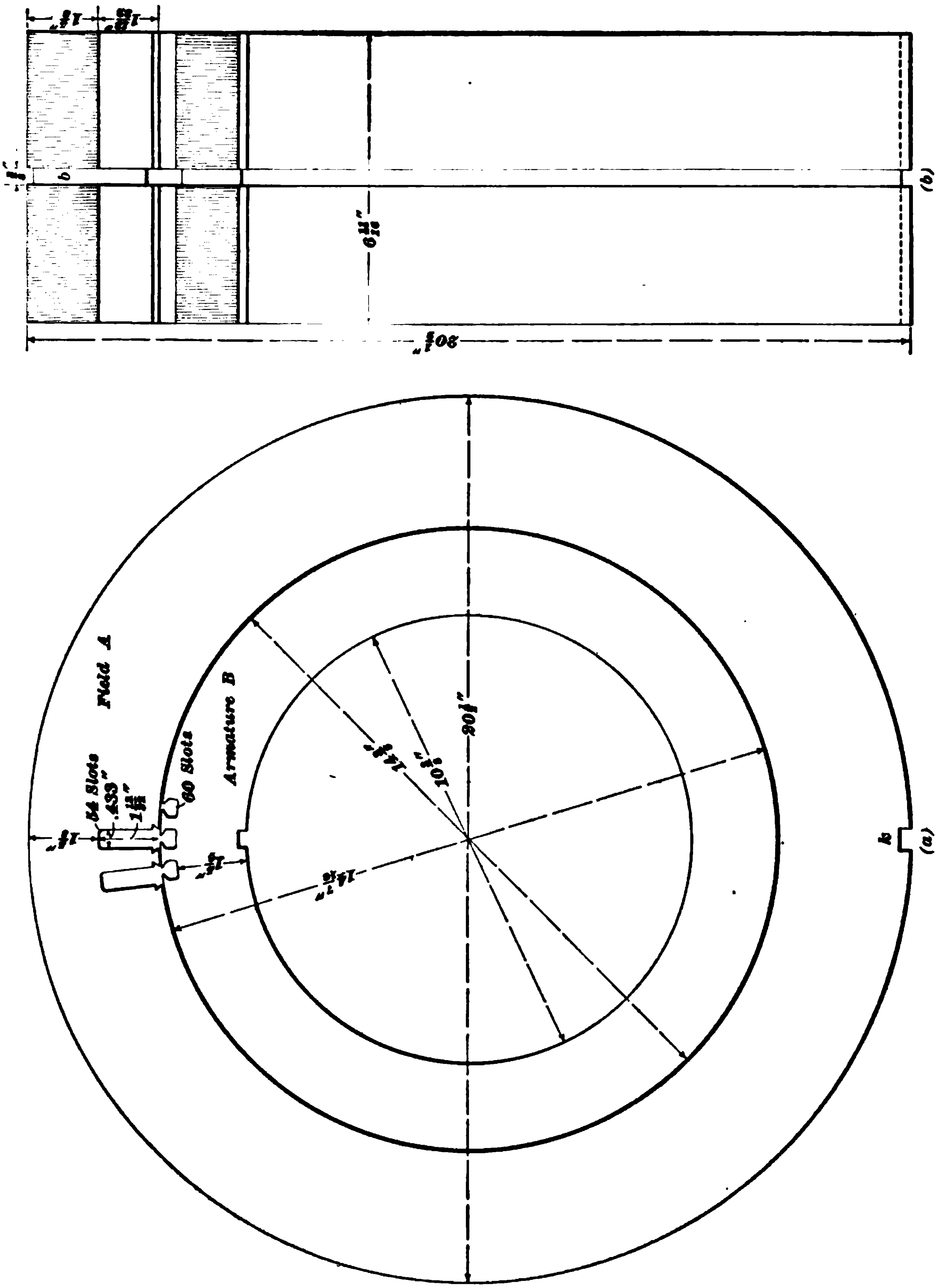


FIG. 20

We will therefore make the dimension d_o, Fig. 18, $1\frac{5}{8}$ inches. The inside diameter is $14\frac{7}{16}$ inches, and the depth of the slots $1\frac{1}{3}\frac{3}{2}$ inches, so that the outside diameter of the stampings for the primary will be $14\frac{7}{16} + 2 \times 1\frac{13}{32} + 2 \times 1\frac{5}{8} = 20\frac{1}{2}$ inches.

The complete dimensions of the primary are shown by (*a*), Fig. 20. A section through one of the primary slots is given at (*b*), showing the air duct *b* and a section of the laminations. The primary laminations are provided with a keyway *k* for holding the stampings in place and bringing the slots into line. There will be 54 slots of the dimensions shown in Fig. 18, equally spaced around the inner periphery.

SECONDARY WINDING

66. The design of the secondary follows largely from that of the primary. The outside diameter is already known, and the length of the secondary core over all parallel to the shaft will be the same as the length of the primary, $6\frac{11}{16}$ inches. We will provide the secondary with a squirrel-cage winding, although a secondary with a regular three-phase **Y** winding might be used if it were desired to insert resistance when starting. It is advisable, though not absolutely necessary, to use a number of slots for the secondary different from that used in the primary, as it tends to prevent dead points at starting. We will therefore try 60 slots for the secondary winding, and see if this number gives a satisfactory design in regard to the size of the slots and bars.

ROTOR CONDUCTORS AND CORE

67. The magnetizing action of the currents in the secondary of an induction motor is, at each instant, equal and opposite to the magnetizing action of the currents in the primary, as is the case in an ordinary transformer. The total volume of current in the secondary may then, for purposes of calculation, be taken equal to that in the primary. In this case we have a total of 540 stator conductors

carrying a current of 27.1 amperes. Hence, the total volume of current is $540 \times 27.1 = 14,634$ ampere-conductors. If, therefore, we use 60 bars on the armature, the current in each bar will be approximately $\frac{14634}{60} = 243.9$ amperes. The voltage that must be generated in the secondary at full load in order to set up this current in the bars will depend on the resistance of the bars, the higher the resistance, the greater being the necessary E. M. F. and the greater the slip. It is desirable, therefore, in order to secure close speed regulation and high efficiency, to make the resistance of the bars as low as practicable. The core losses in the secondary are very small on account of the low frequency of the magnetism in the secondary, so that as far as heating is concerned, we might allow a large I^2R loss in the conductors; an allowance as low as 300 or 400 circular mils per ampere would not likely give rise to any undue heating. We will, however, allow 500 circular mils per ampere, as this larger cross-section will tend toward better speed regulation and higher efficiency. The cross-section of the secondary bars will then be $243.9 \times 500 = 121,950$ circular mils $= .096$ square inch, nearly. The usual practice is to make the secondary slots for squirrel-cage armatures rather broad and shallow, as shown in Fig. 18. This brings the conductors near the surface of the rotating member, and also allows the bars to be placed in the best position for connecting to the end short-circuiting rings. The distance between centers of the secondary slots will be $\frac{45.16}{60} = .753$ inch, or a little over $\frac{3}{4}$ inch. A bar $\frac{7}{16}$ inch by $\frac{7}{32}$ inch has a cross-section of very nearly .096 square inch; a bar of these dimensions will be placed in the slot as shown in Fig. 18. A bar of this size will have a cross-section of approximately 121,800 circular mils, allowing a little for rounding the corners. The width of the bar is $\frac{7}{16}$ inch $= .438$ inch; hence, there is $.753 - .438 = .315$ inch left for the tooth and the insulation. This will allow the teeth to be made $\frac{9}{32}$ inch projected width at the circumference and still leave sufficient space for insulation. Since the

voltage generated in the secondary is very low, a light slot insulation is all that is necessary. In this case there will be room enough for .017 inch insulation around the bar. The secondary slots are made nearly closed at the top, as shown in Fig. 18, and the bars are pushed in from the end.

68. The bars are connected up into closed circuits by means of the short-circuiting rings *r*, Fig. 18, one at each end of the armature, the bars being bolted to the copper rings by means of the flat-headed countersunk bolts *s*. In order to secure good contact, the projecting ends of the bars should be milled to conform with the surface of the ring. The lower the resistance of the end rings, the better, but as the path of the current through these rings is short, there is little advantage gained by putting a large amount of copper into them. We will make the thickness of the rings the same as that of the bars, i. e., $\frac{7}{32}$ inch, and will make the rings $\frac{7}{8}$ inch wide, in order to secure a good contact between them and the bars.

69. The complete dimensions of the stator and rotor have now been determined with the exception of the inner diameter of the rotor disks. The flux through the rotor will be practically the same as that in the stator. The rotor might be worked at a higher magnetic density than the stator without serious loss, because of the low secondary frequency. However, we will use the same density in both, so that the depth of iron under the secondary or rotor slots will be $1\frac{5}{8}$ inches. The total depth of the slots is $\frac{3}{8}$ inch, so that the inner diameter of the rotor is $14\frac{3}{8} - 2\left(\frac{3}{8} + 1\frac{5}{8}\right) = 10\frac{3}{8}$ inches.

HEAT LOSSES

70. The principal dimensions have now been determined, and it remains to be seen whether the motor will deliver its rated output without overheating. In order to do this, we will make an approximate estimate of the

I^2R losses. The I^2R loss in the secondary may be determined approximately as follows: The cross-section of each armature bar as finally adopted will be about 121,800 circular mils. The bars should project a short distance out of the slots, so we will call the length of each bar about $8\frac{1}{2}$ inches. The hot resistance of each bar will then be

$$R = \frac{\text{length in inches}}{\text{circular mils}} = \frac{8.5}{121,800} = .000069 \text{ ohm}$$

The total I^2R loss in the armature will be $(243.9)^2 \times .000069 \times 60 = 246$ watts. There will also be a certain amount of loss in the short-circuiting rings and at the joints, but the total I^2R loss will probably not exceed 300 watts. The outside cylindrical surface of the armature is $45.16 \times 6.687 = 302$ square inches, nearly, which gives a surface of over 1 square inch per watt I^2R loss. The core losses in the secondary will be very small, so that the secondary will carry its load without any danger of overheating.

71. In order to estimate the I^2R loss in the primary at full load, we must first determine the length of a primary turn. There are in all 54 coils and 54 slots, the coils being arranged in two layers. There are six poles, so that if one side of a coil lies in the top of slot No. *1*, the other side will lie in the bottom of slot No. *10*, as shown in the winding diagram, Fig. 22. The coil will then span over $\frac{9}{54}$ of the circumference of the field, as shown in Fig. 21. This figure represents two coils of the field winding in place, the inner face of the field being developed out flat. When the coils are in place, the ends a, a and b, b will project out past the core, forming a cylindrical winding. The ends of the coils are arranged on such a slant that they will fit in as shown without crowding. From this layout of the coils, the length of an average turn can be obtained, and in the present case it is found to be about 36 inches. There are 18 coils in series per phase and 5 turns per coil, making a total of 90 turns. The cross-section of the conductor is $3 \times 8,234$

= 24,702 circular mils, since there are three No. 11 wires in parallel. The resistance per phase will therefore be

$$R = \frac{90 \times 36}{24{,}702} = .131 \text{ ohm, nearly}$$

The I^2R loss per phase will then be $(27.1)^2 \times .131 = 96.2$ watts, and the total I^2R loss in the field will be $96.2 \times 3 = 288.6$, say, 290 watts. The exposed cylindrical

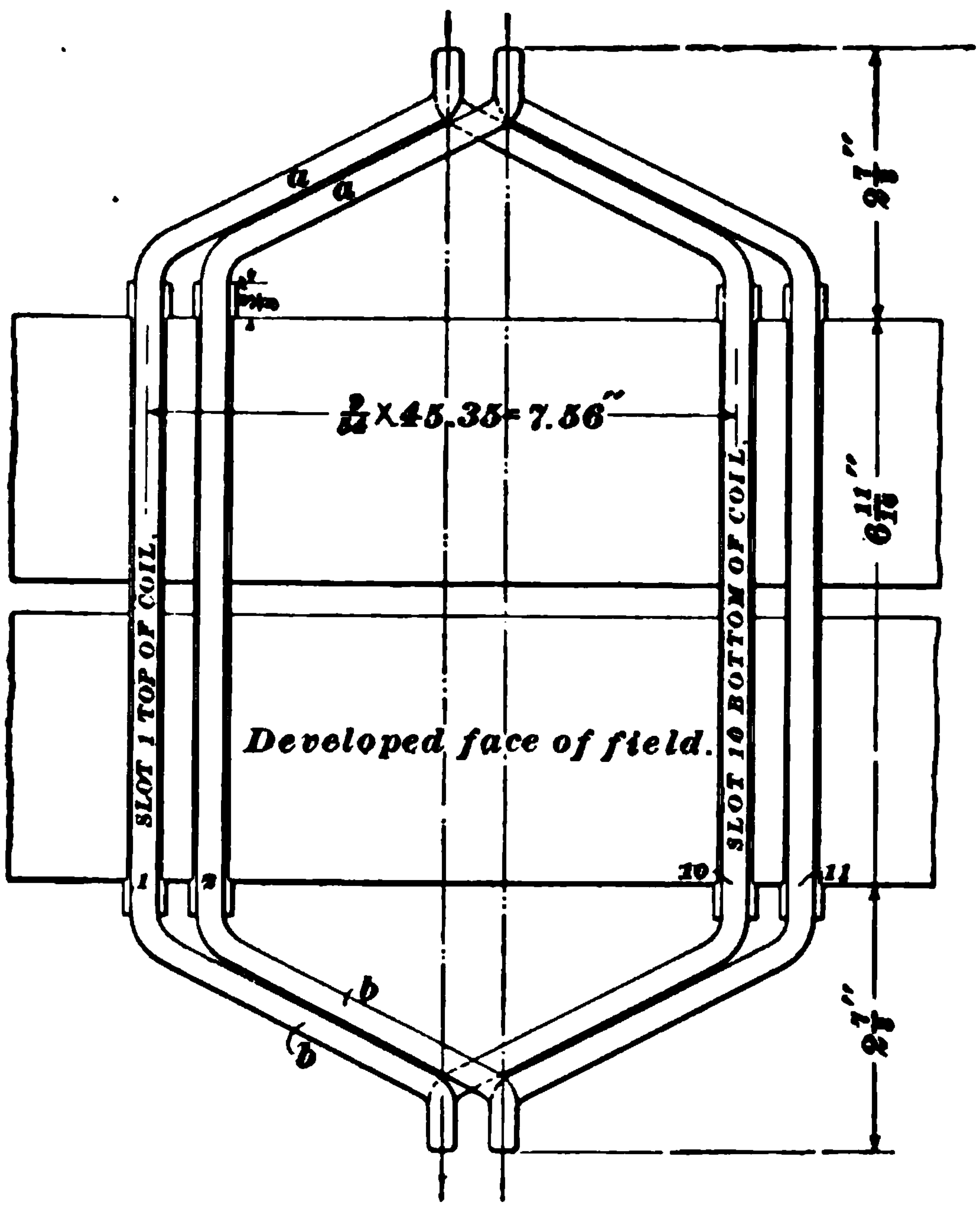
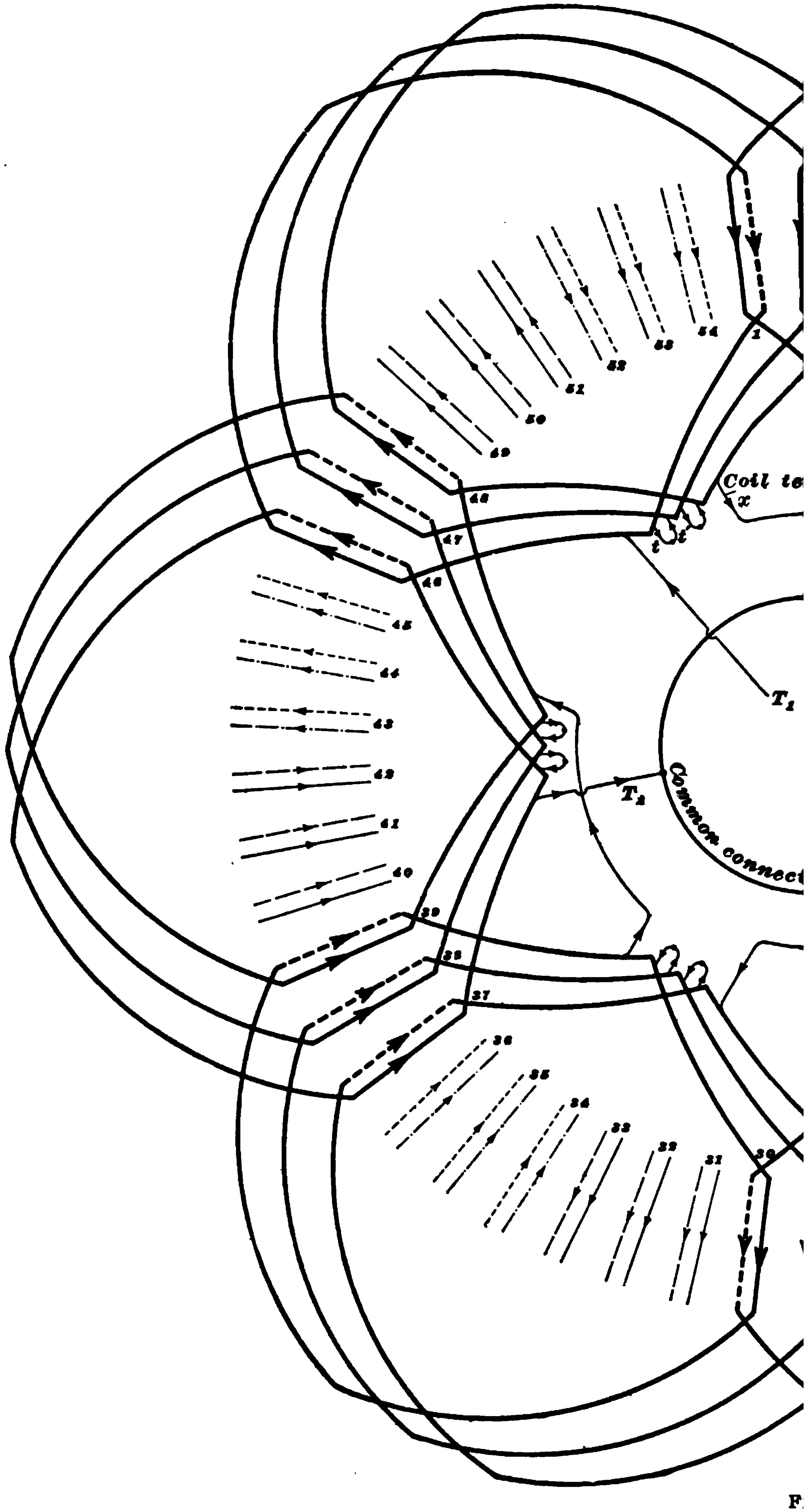


FIG. 21

surface of the field core alone is $20\frac{1}{2} \times 3.1416 \times 6\frac{11}{16} = 430.7$ square inches. The surface exposed by the projecting windings will be approximately 200 square inches, so that there is an effective radiating surface of 630.7 square inches for getting rid of the heat developed in the primary, without counting the radiating surface that would be provided, to a certain extent, by the frame of the machine in


Coil te
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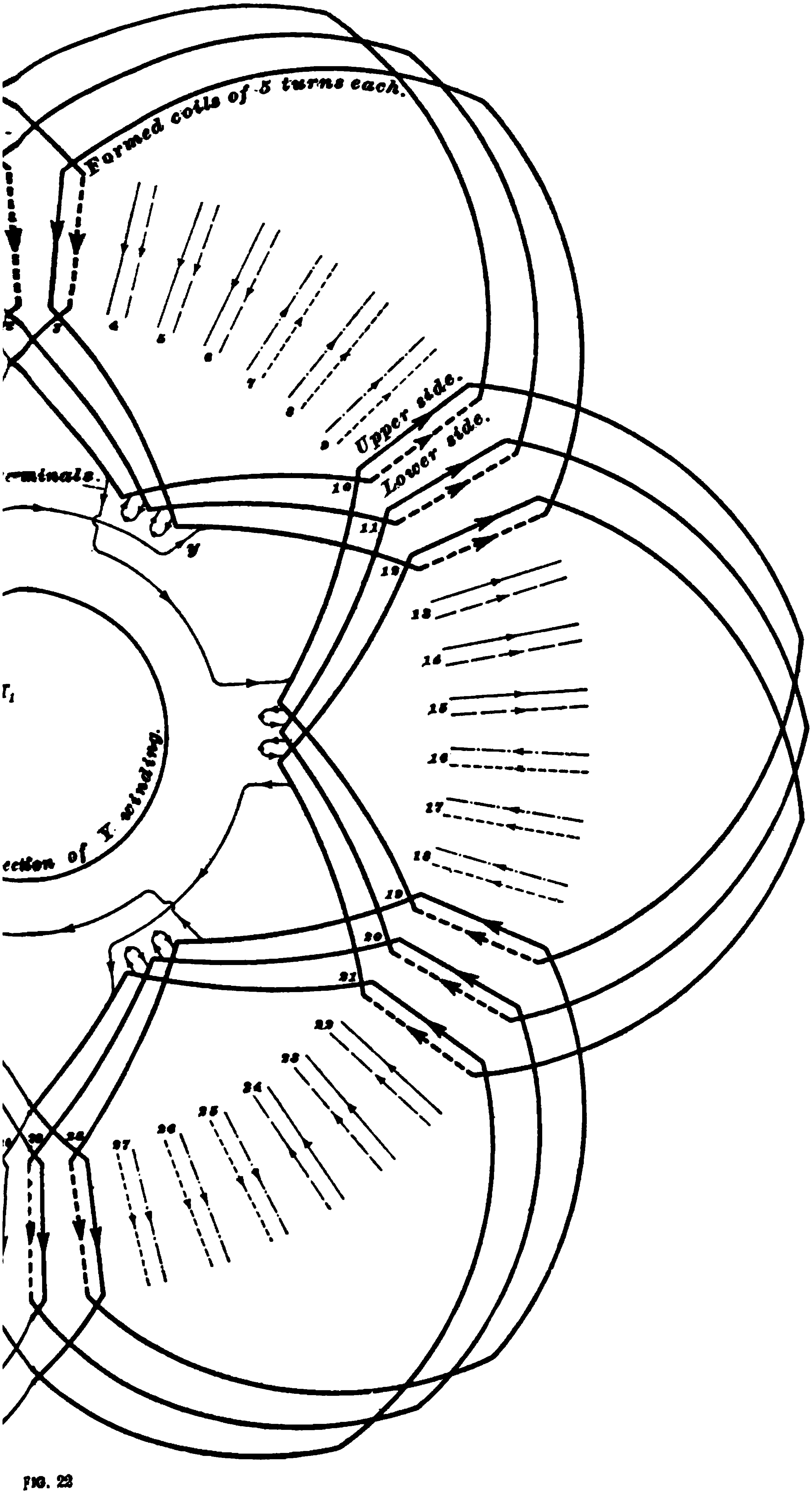


Formed coils of 5 turns each.
Upper side.
Lower side.
erminals.
y
ection of Y winding.

FIG. 22

contact with the field. The radiating surface as a whole, therefore, should be sufficient to get rid of the losses without an undue rise in temperature, especially as the hysteresis loss in the primary core would not be as large as the $I^2 R$ losses, the density being low and the volume of iron comparatively small.

FIELD WINDING AND CONNECTIONS

72. Fig. 22 shows the arrangement of the primary or field winding, one phase being drawn in complete. The groups of conductors for the other two phases are indicated by the light and dotted lines, the connections between them being made in the same way as those for the phase drawn in. The rules governing the connecting up of such a winding have already been explained in connection with polyphase-alternator armatures. Each of the heavy outlined figures represents a field coil of 5 turns; the lighter lines (two to each coil) projecting from the inner point of the coils represent the terminals of the coils. There are 54 slots, or 9 slots corresponding to each pole; hence, the E. M. F.'s in all the conductors in the 9 slots under any one pole will be in the same direction, as shown by the arrowheads. For example, the E. M. F.'s in the conductors in slots *7*, *8*, *9*, *10*, *11*, *12*, *13*, *14*, *15* will all be in one direction, say directed from the front to the back, while those in slots *16*, *17*, *18*, *19*, *20*, *21*, *22*, *23*, and *24* will have their E. M. F.'s in the opposite direction, corresponding to a pole of opposite polarity. The 18 coils shown belonging to one phase must all be connected in series, so that the E. M. F.'s in the conductors in the different slots belonging to this phase will be summed up. Suppose we start with the terminal T_1; we will pass five times around the coil, bridging from slot *46* to slot *1*, in agreement with the arrowheads, and come out at t; we will connect t to t', and go five times around the next coil, finally coming to x and completing the connections of that group of coils. We then pass on to the next group, connecting x to y (so as to agree with the arrows), and so on

around the field until the whole 18 coils are connected in series, finally coming to T_2. We will connect T_2 to the common connection of the Y winding, T_1 being then one of the terminals of the motor that is connected to the line. The other two phases are connected up in exactly the same way, the connections between the terminals of the different phases and the common junction being made according to the rules already given. This winding could also be connected up Δ, the only difference being in the connections of the phase terminals with each other and with the terminals of the machine.

MECHANICAL CONSTRUCTION

ARMATURE

73. The **armature core** is built up in almost exactly the same way as cores for alternator or continuous-current armatures, the disks being mounted on a spider and clamped together by means of end flanges drawn up and held in place by capscrews or bolts. If a wound secondary is used, it is customary to provide the spider with projecting flanges for supporting the winding, as already explained for alternator armatures with distributed windings. Where the squirrel-cage construction is used, no supports are necessary, the bars and short-circuiting ring being stiff enough to hold themselves in place.

SHAFTS

74. **Shafts** for induction motors are usually made exceptionally heavy, considering the power that they must transmit. They should, in general, be heavier than the shafts used for alternators of corresponding speed and output. The air gap in induction motors is so small that a very stiff shaft is required, the slightest bending of the shaft being sufficient to either let the armature touch the field or bring very heavy magnetic pulls on the shaft, due to the shortening of the air gap on one side. The shafts for these motors are

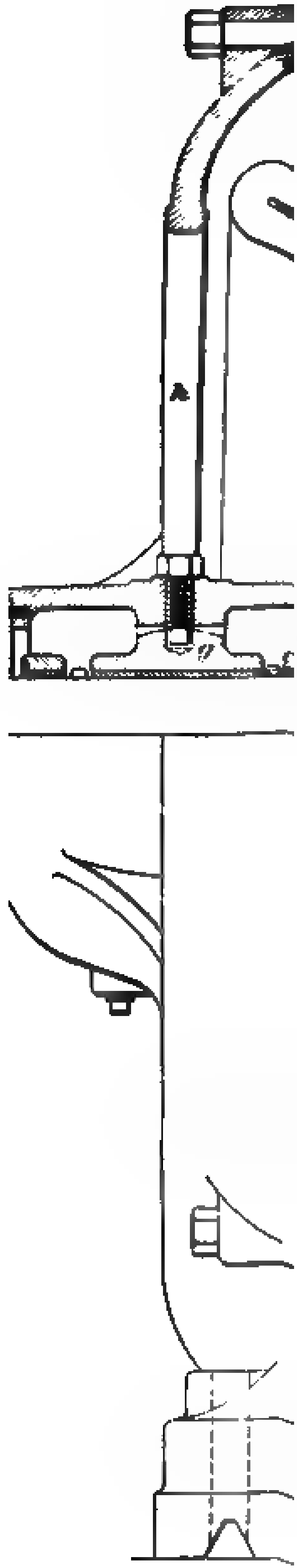
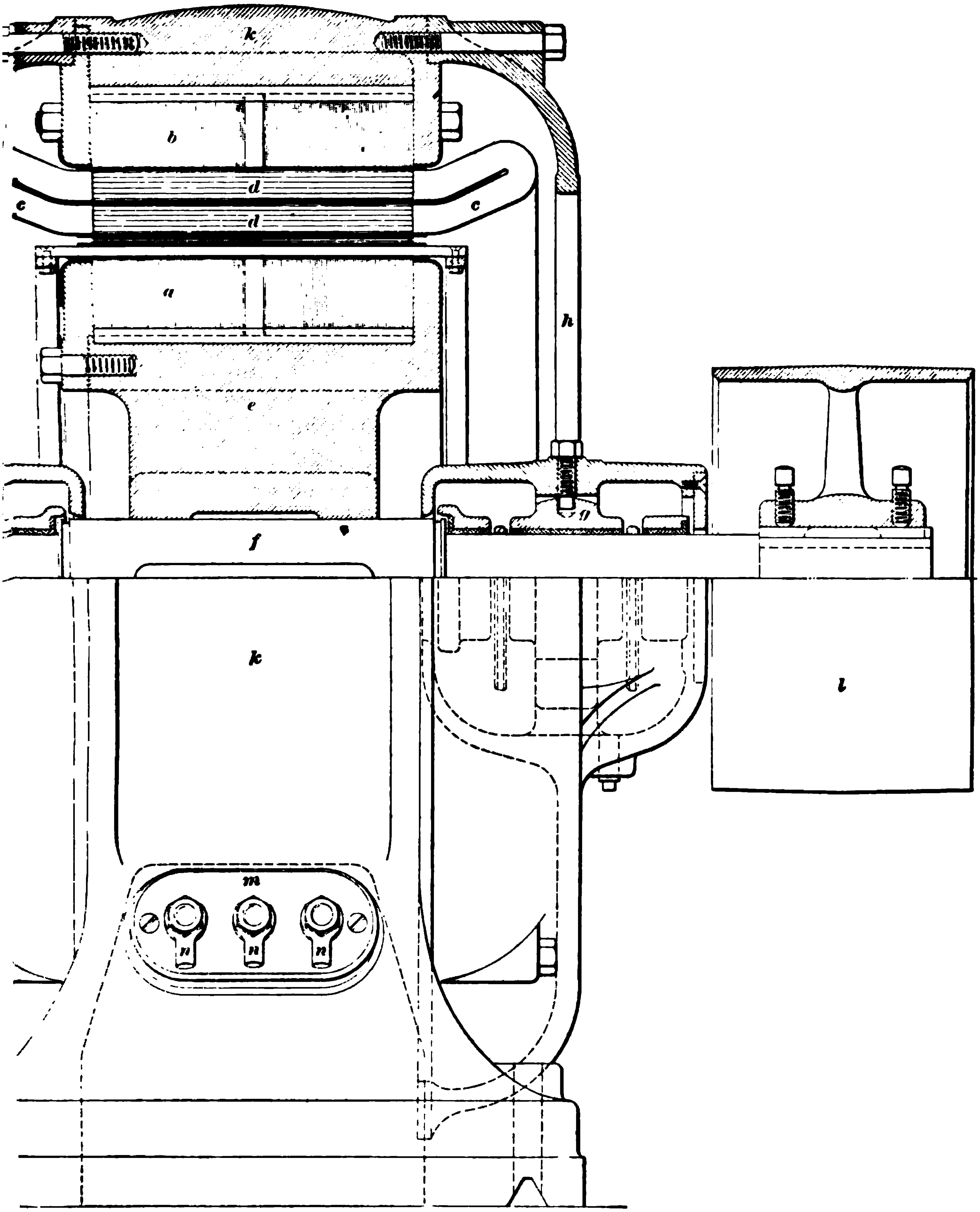


FIG 5


k
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shorter than those required for alternators and continuous-current machines, because no room need generally be allowed for collector rings. Fig. 23 shows the induction motor that has been worked out. This will give an idea as to the style of shaft used for such machines.

FIELD FRAME, BEDPLATE, ETC.

75. The arrangement of the parts of an induction motor of this size will be understood by referring to Fig. 23. In this case the **field frame** forms the main supporting casting of the machine, being provided with feet as shown. It serves the double purpose of supporting the field stampings and forming a base for the machine. In some of the larger sizes of induction motors, the field frame is bolted to a separate bed in the same manner as shown for the field of the alternator. For machines of moderate size, the construction shown in Fig. 23 answers quite well, and is cheaper than that which makes use of a separate bed. The self-oiling bearings are carried by the two end plates *h*, *h*, which are bolted to the field frame, as shown, and carry the bearings *g*, *g* and the shaft *f*, with pulley *l*. These end-bearing supports also serve to protect the field coils *c*. The conductors in the field slot are shown at *d*, *d*, and *b* is a section of the field laminations. The armature laminations *a* are supported by the spider *e* and held by the cap bolts and end flange, as shown. The armature bar is shown projecting from the slot, the ends being bolted to the short-circuiting rings. The field frame *k* is provided with a number of ribs *r*, which are bored out to fit the outer circumference of the stampings. A number of openings *o* are cored in the frame to allow ventilation. The terminals of the field winding are led through the cored openings *p*, *p* to the terminals *n*, which are mounted on the slate terminal board *m*, from which the connections to the line are made. It will be seen that, on the whole, the construction of such a motor is very simple, there being no brushes, brush holders,

collector rings, etc. Fig. 24 shows a perspective view of an induction motor of the same general type as the one worked

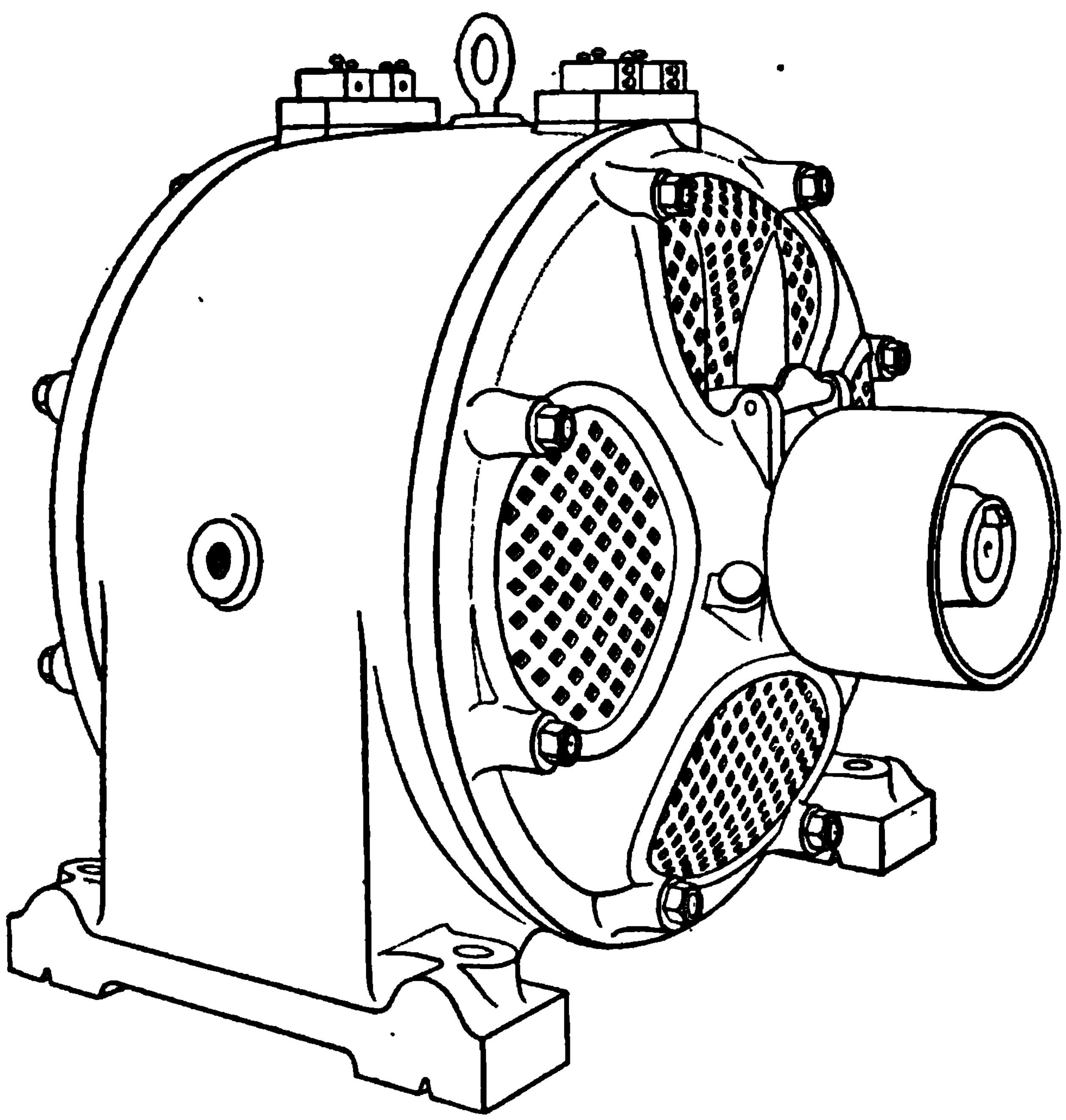


FIG. 24

out. The main mechanical features of Fig. 24 will be understood by referring to Fig. 23, so that further comment is unnecessary.

76. Two-phase and single-phase induction motors are designed in the same way as three-phase machines, the only essential difference being in the arrangement of the windings. The calculation of two-phase armature windings has already been described, and the calculations for a two-phase induction-motor field are made in the same way.

ELECTRIC TRANSMISSION

INTRODUCTORY

1. Electric transmission may be defined as the transferring of power from one point to another by means of electricity. The power so transmitted may be used for any of the numerous applications to which electricity is now adapted, such as operating motors, lights, electrolytic plants, etc. The distance over which the power is transmitted may vary from a few feet, as in factories, to many miles, as in some of the modern long-distance transmission plants.

2. A power-transmission system consists of three essential parts: (*a*) The station containing the necessary dynamos and prime movers for generating the electricity; (*b*) the line for carrying the current to the distant point; and (*c*) the various receiving devices by means of which the power is utilized.

3. Electric transmission may be carried out by using direct current, alternating current, or a combination of the two. Generally speaking, in cases where the transmission is short, direct current is used, though alternating current is now also largely used for short-distance transmission, as, for example, in driving factories. When the distance is long, it is necessary to use alternating current. In cases where the distance is long and where alternating current is not well adapted to the operation of the receiving devices, the current transmitted over the line is alternating, but it is changed to direct current at the distant end and there distributed, thus forming a combination of the two systems. The special applications of electric transmission to railway

and lighting work will be taken up later in connection with those branches of the subject; for the present, the object is only to bring out important points relating to the subject of electric-power transmission generally.

Power transmission is extensively used in connection with water powers that would in many cases be of little use on account of their being located away from railways or commercial centers. It is also coming into extensive use in factories to replace long lines of shafting and numerous belts, which are wasteful of power. Its most important use, however, is in connection with the operation of electric railways, where the power is transmitted from the central station to the cars scattered over the line. The style of apparatus used will depend altogether on the special kind of work that the plant is to do, and the type best adapted for a given service will be described when the different transmission systems are treated later. Power stations will be taken up by themselves; the present Section will be confined to the methods and appliances used for carrying out electrical transmission.

POWER TRANSMISSION BY DIRECT CURRENT

4. Up to within a comparatively recent date, electric transmission for power purposes was carried out by means of the **direct current,** alternating current being used when the power was required for lighting purposes only. Later, however, alternating-current motors and rotary converters came into use, and at the present time, large transmission systems use alternating current for both light and power.

5. Dynamos and Motors Used.—Direct-current dynamos may be of either the constant-current or the constant-potential type. Practically all the current is distributed at constant potential and in America compound-wound dynamos are generally used. The motors used in connection with such constant-potential systems are generally of the shunt or compound type.

6. Simple Power-Transmission System.—About the simplest possible example of electric-power transmission is that shown in Fig. 1. Here a compound-wound dynamo *A* is driven by means of an engine not shown, and sends current through the motor *B* by means of the lines *M*, *M*. The dynamo is driven at constant speed and its series-winding is adjusted so that the pressure at the terminals of the dynamo rises slightly as the current increases, due to the increase of the load on the motor. This slight rise in voltage is to make up for the loss in pressure in the line, as will be explained later. The pressure at the motor remains nearly constant, no matter what load the motor may be carrying, but the current supplied increases as the load is increased. When

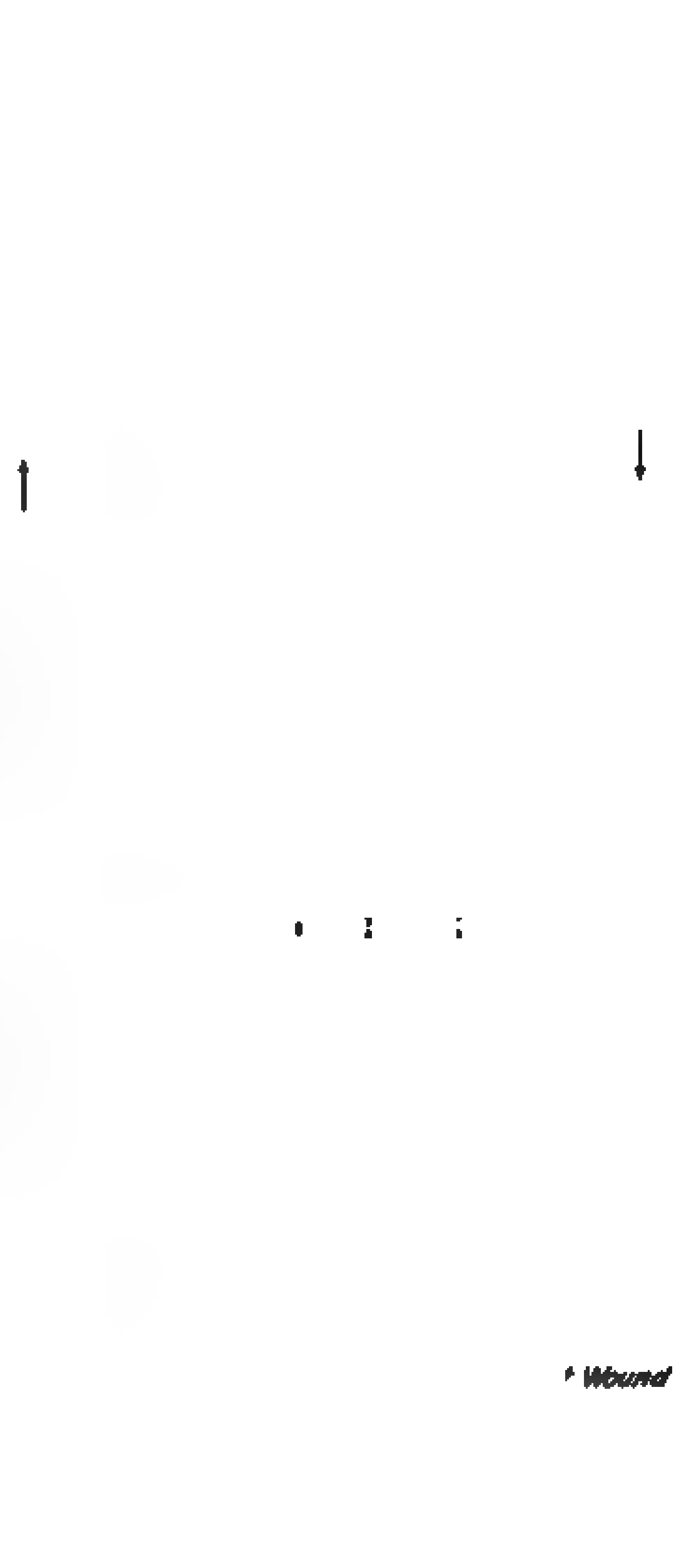


FIG. 1

both lights and motors are operated, such a system will probably use a pressure of 110 or 220 volts at the receiving

end of the circuit; if used for power alone, a pressure of 250 or 500 volts will be employed. It should be mentioned that when the **receiving** end of a circuit is spoken of, the end distant from the station is meant, because this is the end where the various devices, such as lamps, motors, etc., receive their current.

7. Lost Power and Line Drop.—In order that a transmission plant may be efficient, the generating apparatus, line, and motors must be efficient. Dynamos and motors of good make are generally satisfactory as regards efficiency, and the question is, How efficient can the line be made? In answer to this, it might be said that the loss of power in the line could be made as small as we please if expense were no consideration. All conductors, no matter how large, offer some resistance to the current and there is bound to be some loss in power. By making the conductor very large we can make the loss small, because the resistance will be low, but a point is soon reached where it pays better to allow a certain amount of power to be lost rather than to further increase the size of the conductor. The pressure necessary to force the current over the line is spoken of, in power-transmission work, as the **drop** in the line, because this pressure is represented by a falling off in voltage between the dynamo and the distant end of the line.

8. If R is the resistance of the line and I the current flowing, the drop is, from Ohm's law, $e = IR$. The power, in watts, lost in the line is $IR \times I = I^2 R$. The power lost, due to the resistance encountered by the current, reappears in the form of heat. The power generated by the dynamo is equal to the product of the pressure generated by the dynamo and the current flowing; or, if E_1 represents the dynamo pressure, then

$$\text{watts generated} = W_1 = E_1 I \qquad (1)$$

The power delivered at the end of the line is equal to the product of the pressure at the end of the line multiplied by

the current, or, if E_2 represents the pressure at the distant, or receiving, end, then

$$\text{watts delivered} = W_2 = E_2 I \qquad (2)$$

It should be particularly noted at this point that the current I is the same in all parts of the circuit. Thus, in Fig. 1 the same current flows through the motor that flows through the dynamo, unless there is a leakage at some point between the lines, and this would not be the case if the lines were properly insulated. What does occur is a drop or loss in pressure between the station and the receiving end, but there is practically no loss in current except, perhaps, in a few cases where the line pressure is exceedingly high or the insulation unusually bad. This point is mentioned here because the mistaken idea that there is a loss of current in the line is a common one.

9. We have already seen that the number of watts lost in the line is given by the equation $W = I^2 R$.

The lost power must also be equal to the difference between the power supplied and the power delivered, or $W = W_1 - W_2 = E_1 I - E_2 I = I(E_1 - E_2)$.

$E_1 - E_2$ represents the loss of pressure, or the drop, and it is at once seen that the greater the drop, the greater the loss in power. For example, a 5-per-cent. drop in voltage is equivalent to a 5-per-cent. loss of power in the line.

10. In order to transmit power, we must be willing, then, to put up with a certain amount of loss, or what is equivalent, with a certain amount of drop in the line. The amount of drop can be made anything we please, depending on the amount of copper we are willing to put into the line. The percentage of drop allowed is seldom lower than 5 per cent. and not often over 15 per cent. except on very long transmission lines; 10 per cent. is a fair average. In cases where the distribution is local, as, for example, in house wiring, the allowable drop from the point where the current enters the building to the farthest point on the system may be as low

as 1 or 2 per cent. If the drop is excessive, the pressure at the end of the line is apt to fluctuate greatly with changes of load and thus render the service bad. In a few special cases there may be conditions that warrant the use of an excessive drop, but in general the above values are the ones commonly met with.

11. When the loss, or drop, in a circuit is given as a percentage, this percentage may refer either to the voltage at the station end of the line, or the voltage at the receiving end. For example, suppose we take the case where the percentage loss refers to the voltage at the station end, and let

E_1 = voltage at dynamo;
E_2 = voltage at end of line;
$\%$ = percentage loss (expressed as a number, not as a decimal);
e = actual number of volts drop in the line.

Then,
$$E_1 = \frac{100\,E_2}{100 - \%} \qquad (3)$$

And
$$e = \frac{100\,E_2}{100 - \%} - E_2 \qquad (4)$$

EXAMPLE.—The voltage at the end of a lighting circuit is to be 110 and the allowable drop is to be 3 per cent. of the dynamo voltage. (*a*) What will be the dynamo voltage? (*b*) What will be the actual drop, in volts, in the circuit?

SOLUTION.—(*a*) We have $E_1 = \frac{100 \times 110}{100 - 3} = 113.4$. Ans.

(*b*) The drop $e = \frac{100 \times 110}{100 - 3} - 110 = 3.4$ volts. Ans.

12. It is frequently more convenient to express the loss as a percentage of the power delivered at the end of the line. For example, if the voltage at the end of the line were 110, and the loss were to be an amount equivalent to 3 per cent. of the power delivered, instead of 3 per cent. of the power generated, it would mean that the allowable drop was 3 per cent. of 110, or 3.3 volts, instead of 3.4 volts. Railway generators are commonly spoken of as being adjusted for

10 per cent. loss when they are wound so as to generate 500 volts at no load and 550 volts at full load; i. e., 50 volts, or 10 per cent. of 500, is allowed as drop in the line, 500 being the voltage at the end of the line. In expressing the loss as a percentage, then, it should be distinctly understood as to whether this percentage refers to the power generated or the power delivered, otherwise there is liable to be confusion. The best way is to express the drop directly in volts and then there can be no doubt as to what is meant. In what follows, we will, when expressing the loss as a percentage, refer to the power delivered unless it is otherwise specified, as this method is now very generally followed.

LINE CALCULATIONS

13. Calculations for Two-Wire System.—We are now in a position to look into the method of determining the size of wire necessary for a given case. First consider the simple transmission system, shown in Fig. 1. The problem of determining the size of a line wire usually comes up about as follows: Given a certain amount of power to be transmitted over a given distance with a given amount of loss; also, given the required terminal voltage; determine the size of line wire required. The whole problem of determining the size of line wire simply amounts to estimating the size of wire to give such a resistance that the drop will not exceed the specified amount. All the formulas for this purpose are based on Ohm's law, and are simply this law arranged in a more convenient form to use. There have been a large number of these formulas devised, each for its own special line of work, and the one that is derived below is given because it is as generally applicable as any.

14. In the first place, if the watts or horsepower to be delivered and the voltage at the end of the line are given, we can at once determine the current, because

$$I = \frac{W_2}{E_2} \qquad (5)$$

in which W_s is the power delivered. Furthermore, the drop e in the line is known or specified, and since

$$e = IR \qquad \textbf{(6)}$$

or $R = \frac{e}{I}$, the resistance R of the line is easily determined.

15. Referring to Fig. 1, it is seen that the total length L of line through which the current flows is twice the distance from the dynamo to the end of the line. It has already been shown that the resistance of a wire is directly proportional to its length and inversely proportional to the area of its cross-section, or $R = \frac{KL}{A}$, where K is a constant that depends on the units used for expressing the length L and the area of cross-section A. In practice, it is generally most convenient to have the length L expressed in feet and the area A in circular mils. When these units are used, the quantity K is the resistance of 1 **mil-foot** of wire; i. e., the resistance of 1 foot of wire $\frac{1}{1000}$ inch in diameter. If the area of cross-section of the wire were only 1 circular mil, it is evident that the resistance of L feet of it would be KL, and if the area of the wire were A circular mils, its resistance would be $\frac{KL}{A}$.

The resistance of 1 mil-foot of copper wire, such as is used for line work, may be taken as 10.8 ohms. This resistance will, of course, vary with the temperature and also with the quality of the wire used, but the above value is close enough for ordinary line calculations. The following formula may then be used for calculating the resistance of any line:

$$R = \frac{10.8\,L}{A} \qquad \textbf{(7)}$$

where R = resistance in ohms;
L = length of line in feet (total length, both ways);
A = area of cross-section in circular mils.

16. What is usually desired is the area of the wire required for the transmission, not the resistance, and by combining formulas **6** and **7** this can be obtained.

We have $$e = IR,$$

but $$R = \frac{10.8\,L}{A};$$

hence, $$e = \frac{10.8\,L\,I}{A},$$

or $$A = \frac{10.8\,L\,I}{e} \qquad (8)$$

Expressing this formula in words, the required area of cross-section in circular mils

$$= \frac{10.8 \times \text{length of line in feet} \times \text{current in amperes}}{\text{drop in volts}}$$

This rule for determining the size of wire for a given transmission may be written as follows:

Rule.—*Take the continued product of 10.8, the total length of the line in feet, and the current in amperes; divide by the drop in volts, and the result will be the area of cross-section in circular mils.*

17. It will be noticed that the size of wire has been determined by making it of such dimensions that the drop will not exceed the allowable amount. In other words, the drop has been made the determining factor and no attention has been paid to the current-carrying capacity of the wire. If the distance were very short and the drop allowed were large, the size of the wire as given by the formula might be such that it would not carry the current without greatly overheating. This is an important consideration where wires are run indoors, because the distances are then short and the rise in temperature of the wire needs to be carefully considered, owing to the fire risk. This point will be taken up in connection with interior wiring. For line work such as we are now considering, the distances are usually so long that the size of wire as determined by the allowable drop is nearly always much larger than would be necessary to carry the current without overheating.

18. The formula just given is also often written in the form

$$A = \frac{21.6\,D\,I}{e} \qquad (9)$$

where D is the distance (one way) from the station to the center where the power is delivered. Evidently, D is only one-half the length of wire through which the current flows; i. e., $L = 2\,D$; hence the constant 21.6 is used instead of 10.8.

19. Formulas **8** and **9** may be applied to a large number of cases if care is taken to see that the proper values are substituted. The length L or distance D must always be expressed in feet. The use of the formulas will be illustrated in connection with the following examples. Table I, giving the area in circular mils of the various sizes of wire according to the Brown & Sharpe gauge, is here inserted for convenient reference in connection with the examples.

TABLE I

SECTIONAL AREA OF B. & S. WIRES

No. B. & S.	Cross-Section Circular Mils	No. B. & S.	Cross-Section Circular Mils	No. B. & S.	Cross-Section Circular Mils
0000	211,600	11	8,234	25	320
000	167,805	12	6,530	26	254
00	133,079	13	5,178	27	202
0	105,535	14	4,107	28	160
1	83,694	15	3,257	29	127
2	66,373	16	2,583	30	101
3	52,634	17	2,048	31	79.7
4	41,742	18	1,624	32	63.2
5	33,102	19	1,288	33	50.1
6	26,251	20	1,022	34	39.7
7	20,816	21	810	35	31.5
8	16,509	22	642	36	25.0
9	13,094	23	509	37	19.8
10	10,381	24	404	38	15.7

EXAMPLE 1.—In Fig. 1 the pressure at the receiving end of the line is to be 500 volts, and 40 kilowatts is to be transmitted with a drop of 50 volts. The distance from the station to the end of the line is 3 miles. Calculate the cross-section of wire necessary and give the nearest size B. & S. that will answer.

SOLUTION.— 40 K. W. = 40,000 watts; hence, current $= \frac{40000}{500}$ = 80 amperes. The distance from the station to the end of the line is 3 mi., but the current has to flow to the end and back again, so that the length of line L through which the current flows is 6 mi., or 31,680 ft. Applying formula 8,

$$A = \frac{10.8 \times 31,680 \times 80}{50} = 547,430 \text{ circular mils, nearly. Ans.}$$

This is considerably larger than any of the B. & S. sizes, so that a stranded cable would be used.

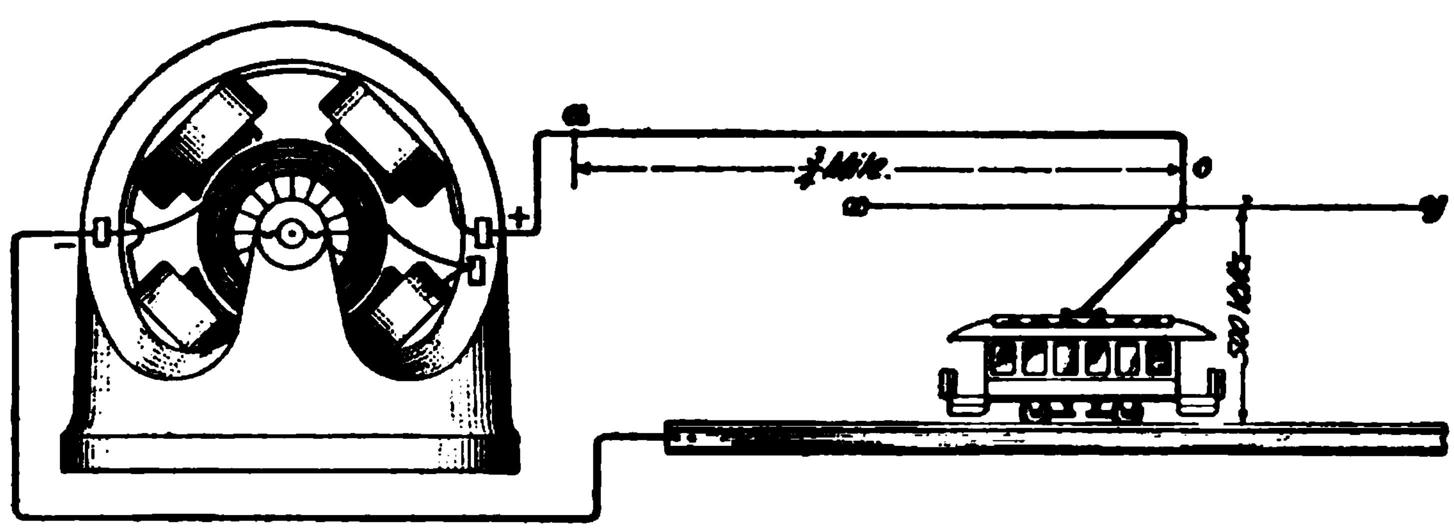


FIG. 2

EXAMPLE 2.—It is desired to transmit 20 horsepower over a line ½ mile long with a drop of 10 per cent. of the voltage at the receiving end. The voltage at the end of the line is to be 110. Find the size of wire required.

SOLUTION.— 20 horsepower = 20 × 746 watts; hence,

$$\text{current} = \frac{20 \times 746}{110} = 135.6 \text{ amperes}$$

The drop is to be 10 per cent. of the voltage at the receiving end; hence, drop $e = \frac{110 \times 10}{100} = 11$ volts. The length L is 1 mi., since the distance from the station to the end is ½ mi., and applying formula 8,

$$A = \frac{10.8 \times 5,280 \times 135.6}{11} = 702,950 \text{ circular mils, nearly. Ans.}$$

This also would call for a large cable.

EXAMPLE 3.—Fig. 2 shows a simple transmission system as used in connection with a street railway. The feeder $a\,c$ runs out from the station and taps into the trolley wire $x\,y$ at the point c. The pressure

between the trolley and track at the point c is to be 500 volts, and the drop in the feeder is to be 10 per cent. of the voltage at the car when a current of 60 amperes is being supplied. The current returns through the track, and we will suppose in this case that the resistance of the return circuit is negligible. Required the cross-section of the feeder $a\,c$.

Solution.—In this case the drop takes place altogether in the wire $a\,c$, because the resistance of the return circuit through the rails is taken as zero; hence, the length L used in the formula will be $\frac{3}{4}$ mi., or 3,960 ft., and not twice this distance, as in the previous examples. The drop in voltage will be $e = \frac{500 \times 10}{100} = 50$, and since the current is 60 amperes, we have

$$A = \frac{10.8 \times 3{,}960 \times 60}{50} = 51{,}322 \text{ circular mils. Ans.}$$

By referring to the wire table, it will be found that this is nearly a No. 3 B. & S.

20. In making line calculations, it seldom happens that the calculated value will agree exactly with any of the sizes given in the wire table. It is usual in such cases to take the next larger size, unless the smaller size should be considerably nearer the calculated value. Generally, the load operated on a line always tends to increase, because business increases, and it is better to have the line a little large, even if it entails a slightly greater cost when the line is erected.

21. Formula **8** may also be used for determining the drop that will occur on a given line with a given current. In this case the formula is written,

$$\text{volts drop} = e = \frac{10.8\,L\,I}{A} \qquad \textbf{(10)}$$

Example.—Power is transmitted over a No. 3 B. & S. line for a distance of 4,000 feet. What will be the drop in the line when a current of 30 amperes is flowing?

Solution.—The length of wire through which the current flows is $2 \times 4{,}000 = 8{,}000$ ft. The cross-section of a No. 3 B. & S. wire is 52,634 circular mils; hence,

$$\text{volts drop} = \frac{10.8 \times 8{,}000 \times 30}{52{,}634} = 49.2. \text{ Ans.}$$

EXAMPLES FOR PRACTICE

1. A dynamo delivers current to a motor situated 850 yards distant. The current taken by the motor at full load is 30 amperes, and the pressure at the motor is to be 220 volts. The drop in the line is to be 8 per cent. of the voltage at the receiving end. Required: (*a*) the drop in volts; (*b*) the size of the wire in circular mils and also the nearest size B. & S.

Ans. { (*a*) 17.6 volts; (*b*) 93,886 cir. mils.; use No. 0 wire }

2. A current of 40 amperes is transmitted from a station to a point 1 mile distant through a No. 0 B. & S. wire: (*a*) What will be the drop, in volts, in the wire? (*b*) How many watts will be wasted in the wire?

Ans. { (*a*) 43.2; (*b*) 1,728 }

USE OF HIGH PRESSURE

22. By referring to the first two examples in Art. **19**, it will be noticed that the wire called for is very large, although the amount of power transmitted is not very great nor the distance long. Suppose a fixed number of watts W_2 to be transmitted with a given voltage E_2 at the end of the line; then, the current that must flow through the line is $\frac{W_2}{E_2}$. We have seen that the loss in the line is $I^2 R$; i. e., if the current be doubled the loss becomes four times as great. If, then, the E. M. F. be doubled, we will be able to transmit the same amount of power with one-half the current, and hence with one-quarter the loss. Or, putting it the other way, and supposing that the loss is to be a fixed amount, we can, by doubling the pressure and thereby halving the current, use a wire of four times the resistance. For example, suppose we have to transmit 20 kilowatts at a terminal pressure of 500 volts and that the loss in the line is to be limited to 2 kilowatts. The current would be $I = \frac{20000}{500} = 40$ amperes, and $I^2 R = 2,000$ watts, or $40^2 R = 2,000$; hence, $R = \frac{2000}{1600} = 1.25$ ohms. Now, suppose that a terminal pressure of 1,000 volts instead of 500 is used and that the same amount of power is transmitted with the same number of watts loss as before. The current will now be $I = \frac{20000}{1000} = 20$ amperes, and $I^2 R = 2,000$ watts, as

before. We will then have $20^2 R = 2{,}000$; $R = \frac{2000}{400} = 5$ ohms.

In other words, *for the same amount of loss and for the same amount of power delivered, the allowable resistance of the line can be made four times as great if the pressure is doubled.* Since the length is supposed to be the same in both cases, this

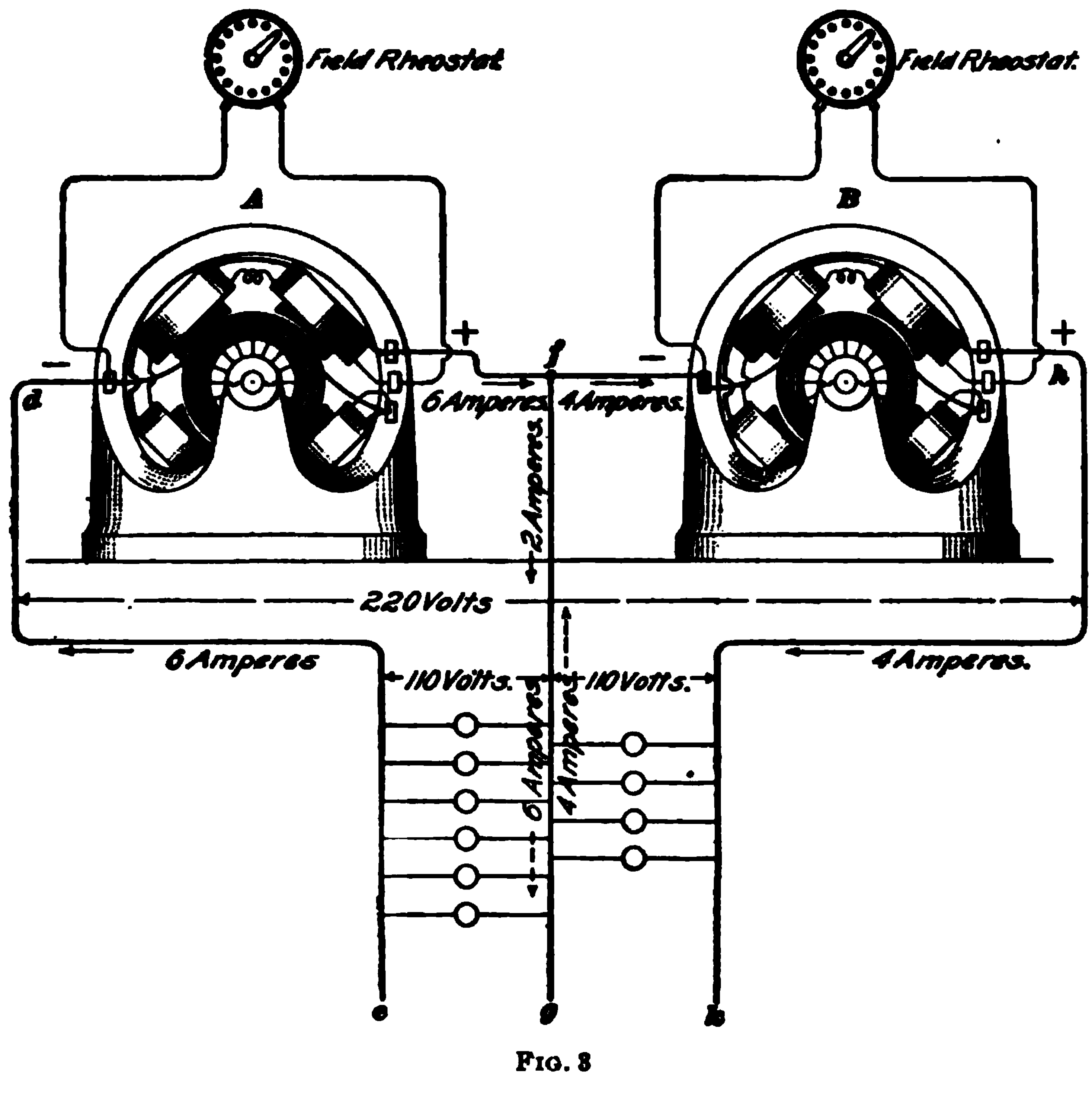


Fig. 8

means that doubling the pressure makes the amount of copper required just one-fourth as great. If the pressure were increased threefold, the amount of copper required would be one-ninth as great, other things being equal. This may be stated as follows: *For the same amount of power delivered and for the same loss in power, the amount of copper required for transmission over a given distance varies inversely as the square of the voltage.*

23. Edison Three-Wire System.—From the preceding it is seen that an increase in the voltage results in a large decrease in the amount of copper required. Incandescent lighting was first carried out at a pressure of 110 volts, but this pressure rendered the use of large conductors necessary, and systems were therefore brought out that would permit the use of a higher pressure. In street-railway work, a pressure of about 500 volts soon became the standard, because this appeared to be the limit to which the voltage could be pushed for this class of work without danger to life.

The **Edison three-wire system** allows current to be supplied at 110 volts, although the transmission itself is really carried out at 220 volts, and therefore results in a large saving in copper over the 110-volt system. The three-wire system is shown in Fig. 3. Two compound dynamos *A* and *B* are connected in series across the two lines *d e* and *h k*. Each dynamo generates 110 volts, so that the pressure between the two outside wires is 220 volts, because the two machines are connected in series. A third wire, called the *neutral*, is connected to the point *f* between the machines, so that between the lines *d e* and *f g* there is a pressure of 110 volts, and between *f g* and *h k* a pressure of 110 volts also.

24. In order to illustrate the action of such a system, suppose there are six 32-candlepower lamps on one side and four on the other, each lamp taking, say, 1 ampere. A current of 4 amperes will flow from the positive side of *B* through the line *h k* and through the lamps to the neutral wire. At the same time, a current of 6 amperes will tend to flow out from the positive pole of *A* over the line *f g* through the left-hand set of lamps and back through *e d*, as shown by the arrows. In the neutral wire there is a current of 6 amperes tending to flow in one direction and a current of 4 amperes tending to flow in the other direction, the result being that the actual current is the difference between the two, or 2 amperes, as shown by the full arrow; or, looking at it in another way, there is 4 amperes flowing directly across from *h k* to *d e* and 2 amperes flowing

from A through the neutral wire fg and back through ed to A, thus making 6 amperes in the line ed. If the currents taken by the two sides were exactly balanced, no current would flow in the neutral wire and there would be practically a 220-volt, two-wire transmission. In any case, the current in the neutral wire is the difference between the currents in the two sides, and its direction will depend on which side is the more heavily loaded.

25. A three-wire system should always be installed so that the load on the two sides will be as nearly balanced as possible. The simplest way to estimate the size of the conductors is to first calculate the size of the outside wires,

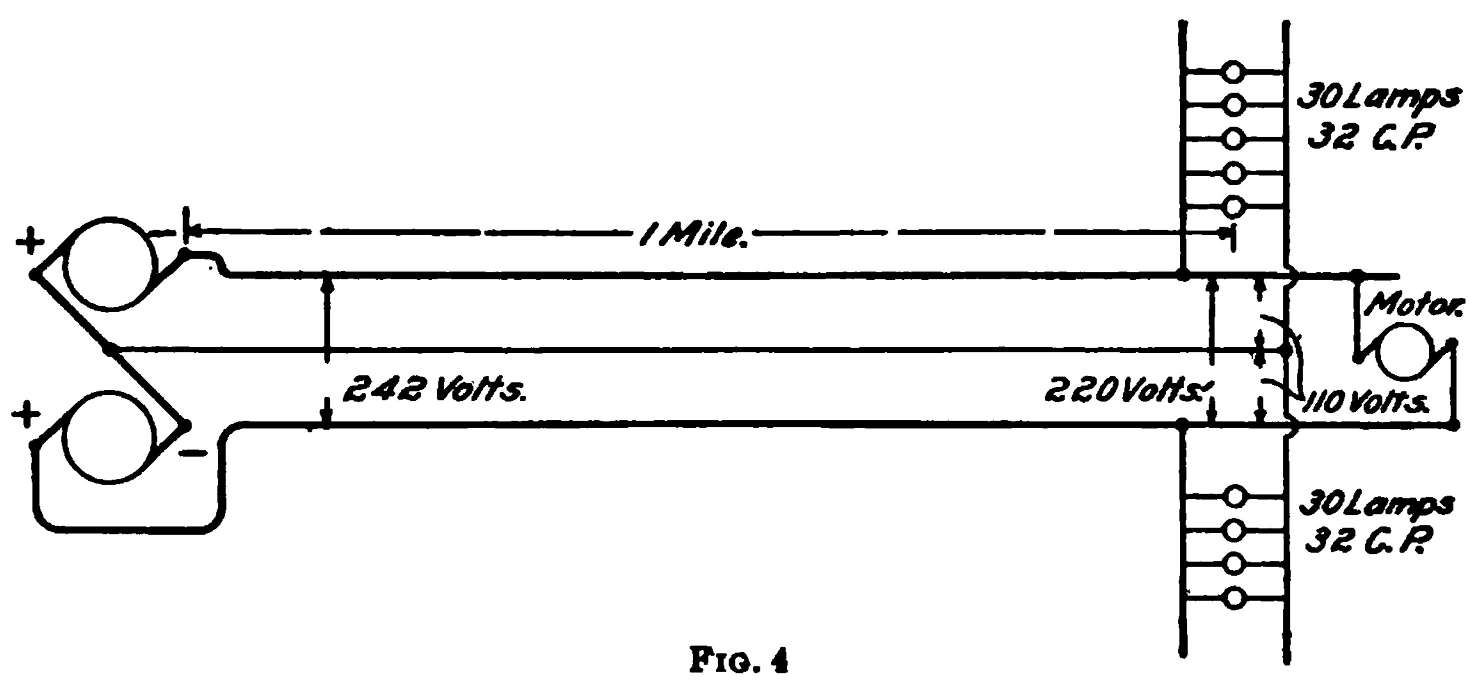


FIG. 4

treating it as if it were a 220-volt, two-wire system. When motors are operated on the three-wire system, they are usually wound for 220 volts and connected across the outside lines. The following example will illustrate the method of calculating the wires for a three-wire transmission:

EXAMPLE.—Two dynamos deliver power over a distance of 1 mile to sixty 32-candlepower lamps, thirty lamps on each side of the circuit, as shown in Fig. 4. A motor that requires a current of 40 amperes is also connected across the outside wires. Each lamp requires a current of 1 ampere, and the pressure at the lamps is to be 110 volts. Calculate the size of wire required for the two outside conductors if the drop in pressure is not to exceed 10 per cent. of the voltage at the end where the power is delivered.

SOLUTION.—The first thing to determine is the current. Thirty lamps are connected on each side and these lamps are connected in

multiple, each taking 1 ampere. The current in the outside lines due to the lamps is, therefore, 30 amperes. The motor is connected directly across the outside lines; hence, the current due to the motor is 40 amperes, and the total current in the outside lines is 70 amperes. The pressure across the outside wires must be 220 volts at the end of the line, because the pressure at the lamps is to be 110. The drop in the outside wires is, therefore, $220 \times .10 = 22$ volts. The length of the outside wires is 2 mi., or 10,560 ft. Applying formula **8**,

$$\text{circular mils} = \frac{10.8 \times 10{,}560 \times 70}{22} = 362{,}880. \quad \text{Ans.}$$

This would require a stranded cable.

26. The neutral wire is often made one-half the cross-section of the outside wires, though practice differs in this respect. It is seldom, however, made less than one-half, and in a number of cases it is made equal in cross-section. Of course, if the load could be kept very nearly balanced at all times, a small neutral wire would be sufficient, but it is impossible to keep the load balanced, and hence it is usual to put in a neutral of at least one-half the cross-section of the outside wires. In the above example, a No. 000 wire would probably be large enough for the neutral. For distributing mains, where there is much liability to unbalancing, the neutral is made equal in size to the outside wires. In some special cases, three-wire systems are arranged so that they can be changed to a two-wire system by connecting the two outside wires together to form one side of the circuit, the neutral wire constituting the other. If this is done, the neutral would have to carry double the current in the outside wires and would be made twice as large as the outside wires.

27. Since the outside wires are only $\frac{1}{4}$ the size required for the same power delivered by means of the two-wire, 110-volt system with the same percentage of loss, it follows that, even if the neutral wire be made as large as the outside wires, the total amount of copper required is only $\frac{1}{4} + \frac{1}{8}$, or $\frac{3}{8}$ of that required for the two-wire, 110-volt system. The amount of copper in the neutral wire is only $\frac{1}{8}$ that required for the two-wire system, because it has $\frac{1}{4}$ the cross-section and its total length is $\frac{1}{2}$ that for the two-wire system.

28. From the preceding it is seen that the three-wire system of distribution effects a considerable saving in copper, owing to the use of a higher pressure. Three-wire systems operating 220-volt lamps with 440 volts across the outside wires have been introduced with considerable success, thus making a still further reduction in copper. The tendency has naturally been to use as high pressure as possible, but there are grave difficulties in the way of transmitting current at high pressure by means of direct current. These difficulties may be classed under the heads (*a*) difficulty of generating direct current at high E. M. F.; and (*b*) difficulty of utilizing direct current at high pressure after it has been generated.

29. Machines for the generation of direct current must be provided with a commutator, and this part of a well-designed machine gives comparatively little trouble if the pressure generated does not exceed 700 or 800 volts; beyond this point, it becomes a difficult matter to make a machine that will operate without sparking. Moreover, in direct-current dynamos, the armature winding has to be divided into a large number of sections or coils, and the numerous crossings of these coils make it exceedingly difficult to insulate such armatures for high pressures.

30. Even if it were possible to generate high-pressure direct current, it would be difficult to utilize it at the other end on account of the danger to life. About 500 to 600 volts is as high as it has been found safe to operate street railways, the consideration of safety setting this limit on the pressure used. Moreover, it is just as difficult to build motors for high-pressure direct current as it is dynamos, and for most purposes the high-pressure current would have to be reduced to low pressure before it could be utilized with safety at the distant end of the line. This transformation could be effected by using a high-voltage motor to drive a low-voltage dynamo. In some cases, these two machines might be combined into one having an armature provided with two windings and two commutators, this armature being arranged so as to revolve

in a common field magnet. The high-tension current from the line is led into one winding through one commutator and drives the machine as a motor. The second set of windings connected to the other commutator cuts across the field and sets up the secondary E. M. F., thus applying current to the low-pressure lines. A machine of this kind is known as a **dynamotor.** It is thus seen that the transformation of direct current from high pressure to low pressure involves the use of what is essentially a high-pressure, direct-current motor—a piece of machinery that is liable to give more or less trouble for the reasons already stated.

SPECIAL THREE-WIRE SYSTEMS

31. The ordinary three-wire system requires two dynamos, and a number of special systems have been devised whereby a three-wire system may be operated from a single machine. Some of these systems will be found described in

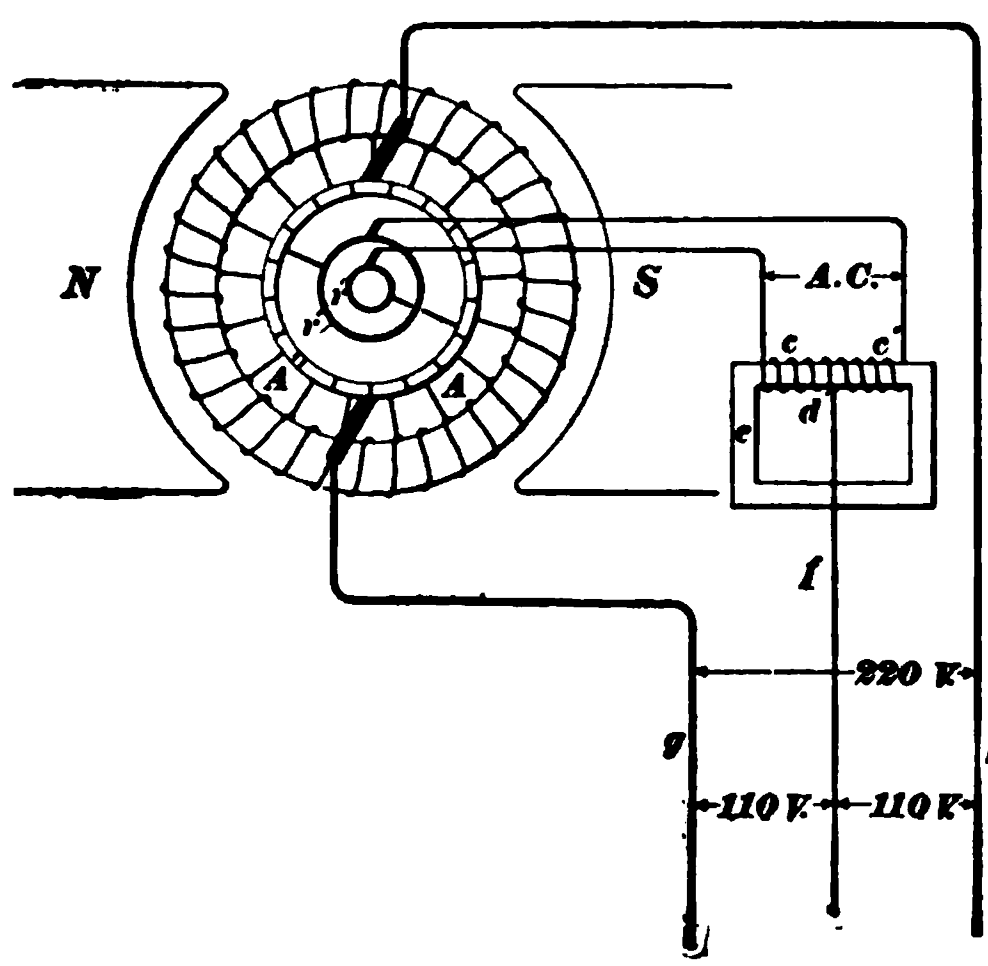


FIG. 5

connection with *Electric Lighting*. Perhaps the most common method, outside of the regular system using two machines, is the use of a single large dynamo connected across the outside wires and a balancing set consisting of a pair of small

machines connected in series across the lines to take care of the unbalanced portion of the load, the neutral wire being connected between the machines, as described in *Electric Lighting*.

32. Dobrowolsky Three-Wire System.—Fig. 5 shows a method invented by Dobrowolsky for running a three-wire system from a single dynamo. *A A* is an ordinary direct-current armature connected to its commutator in the usual manner. Two diametrically opposite points of the winding are connected to the rings *r*, *r'*, and from these connection is made to the terminals of a choke coil. The coils *c*, *c'* have an equal number of turns, and as they are wound on the laminated iron core *e*, they have a high inductance. The pressure applied to the terminals of *c*, *c'* is alternating, because connection is made to the armature winding through slip rings *r*, *r'*. Since the E. M. F. applied to *c*, *c'* is alternating, the coils will not short-circuit the armature because of the counter induced E. M. F. Also, since *c* and *c'* have an equal number of turns, the point *d* will always be at a potential midway between that of the two terminals attached to the collector rings, and if the neutral wire *f* is attached to the junction of *c* and *c'*, the pressure between *f* and either outside wire will be one-half that between the outside wires. If the system becomes unbalanced, a direct current flows through *f*, but the choke coil offers no opposition other than the slight ohmic resistance of *c* and *c'*, because this current is steady and cannot therefore set up a counter E. M. F. Also, if a direct current flows into the coils through *f*, it divides, half flowing through *c* and half through *c'*, and since the two parts of the direct current circulate around the core in opposite directions, the magnetizing effect of the direct current is zero, and it does not therefore interfere with the choking effect that the coils exert on the alternating current.

33. Fig. 6 shows how this system has been applied by the Westinghouse Company. In order to get a more uniform action, the winding is tapped at four points, as in Fig. 6 (*a*), and these points connected to four collector rings in exactly

the same way as for a quarter-phase rotary converter, the commutator and brushes being here omitted. The four rings A_1, B_1, A_2, B_2, Fig. 6 (*b*), are connected to the choke coils C_1, C_2, and the mid-points x of each coil, or rather pair of coils, are connected to the neutral wire a. If the choke coils could be mounted in the armature and revolved with

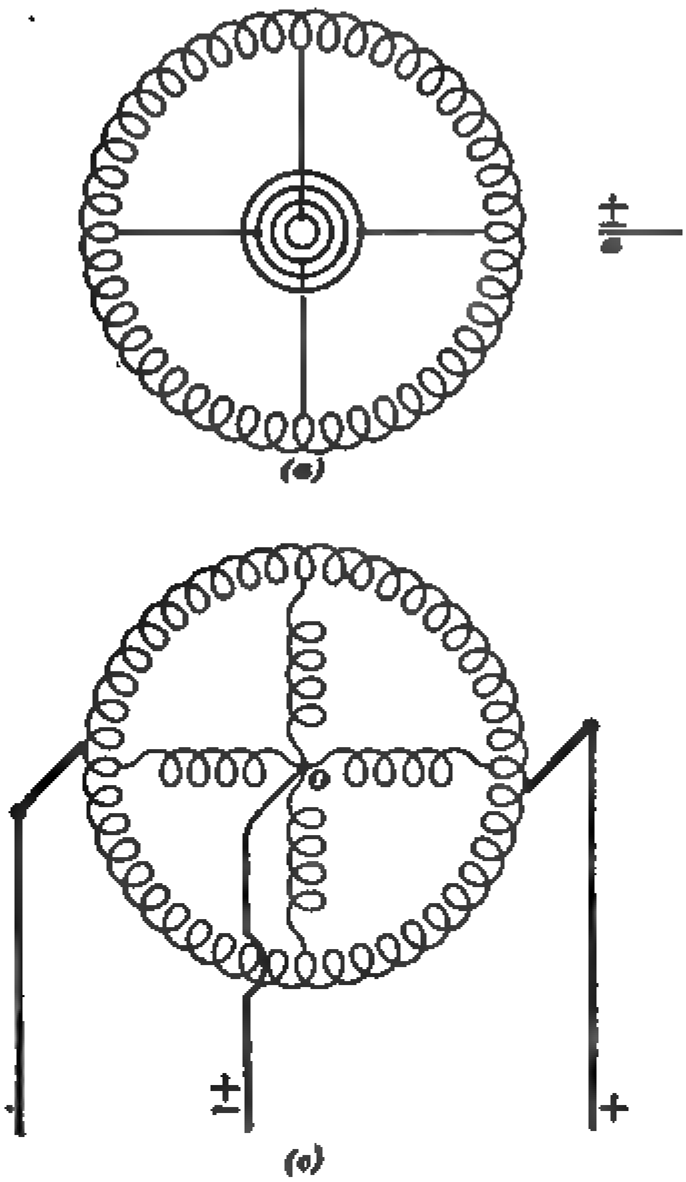


FIG. 6

it, the connections would be equivalent to those shown in Fig. 6 (*c*), and but one collector ring would be required to connect the neutral wire with the neutral point O. In some cases three pairs of choke coils are used connected to six equally spaced points in a manner similar to that shown in Fig. 6 (*a*), each point connecting to a collector ring. The

diagrams are here shown for two-pole machines; for multipolar machines there would be a connection to each ring for each pair of poles.

34. Fig. 7 shows a method of operating a three-wire, direct-current system from two-phase, alternating-current mains. An arrangement of this kind is useful where the greater part of the output of a plant is utilized as alternating current, but where it is desired to use part of it for operating direct-current motors on the three-wire system or supply an existing three-wire, direct-current system from an alternating-current station. *A* and *B* are two transformers with their primaries connected to the two phases and their secondaries connected in series and feeding a two-phase, three-wire rotary converter. The mid-point *C* of the two secondaries is connected to the neutral wire *N*. It is evident that point *C* is always at a potential half way between that of the outside wires, or in other words the pressure between *C* and *D* or *C* and *E* is always half that between *E* and *D*, and the pressure between *N* and *F* or *N* and *G* is half that between *F* and *G*, which is the condition required for a three-wire system.

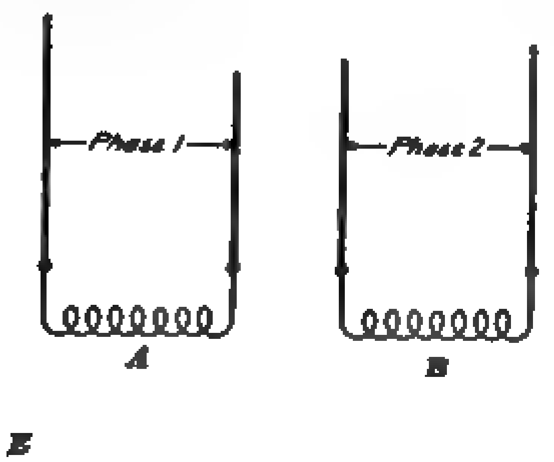


FIG. 7

35. Direct-Current Converter.—Referring again to Fig. 5, it will be seen that instead of driving the armature *A* by means of a belt and thereby operating a three-wire system from a single dynamo, the armature may be driven

by means of current supplied from an outside source. When operated in this way the machine acts as a direct-current converter, and by means of it direct current can be transformed to another direct current at half the voltage, or the current supplied can be delivered as another at twice the original voltage. For example, in Fig. 5, current at 220 volts can be supplied at the brushes and a current of twice the amount delivered at 110 volts. Or, if current is supplied at 110 volts to one pair of the three terminal wires, it will be converted to a current of one-half the volume at 220 volts. Direct-current converters have been used in some cases where it is desired to operate 250-volt motors from a 500-volt power circuit. These machines have so far been used but little for this class of work, motor dynamos or dynamotors having been used instead.

POWER TRANSMISSION BY ALTERNATING CURRENT

36. The difficulties encountered in the generation and utilization of high-tension direct current led engineers to adopt **alternating current** for places where the power had to be transmitted over considerable distances. At first, alternating current was used for lighting work only, because the single-phase alternators first introduced were not capable of readily operating motors, although they were quite satisfactory for the operation of incandescent lamps. With the introduction of polyphase alternators along with the induction motor, the use of alternating current for power purposes became very common, and plants using line pressures as high as 60,000 volts are in regular operation.

37. Alternating current is well adapted for high-pressure work, because not only can it easily be generated, but what is even of greater importance, it can be readily transformed from one pressure to another. The winding of an alternator armature is very simple, no commutator is necessary, and the problem of generating high pressures becomes a

comparatively easy one. In some cases, the current is generated at a low pressure and raised by step-up transformers for transmission over the line. At the distant end it is easily lowered, by means of step-down transformers, to any pressure required for the work to which it is to be put.

SINGLE-PHASE TRANSMISSION

38. The simplest scheme for alternating-current transmission is that which uses a single-phase dynamo; i. e., a machine that generates a single alternating current. In Fig. 8, *A* represents a simple alternator generating current at a high pressure. This current is transmitted over the line to the distant end, where it is sent through the primary of transformer *B*, which lowers the pressure to an amount suitable for distribution to the lamps *l*. The synchronous motor *M* is operated directly from the line, because it can be wound for a high voltage. If, however, this high pressure about the motor should for any reason be objectionable, step-down transformers could be used. As already mentioned, such systems are installed for lighting work almost exclusively. At first a pressure of 1,100 volts at the alternator, or about 1,000 at the end of the line, was commonly used. Later, pressures of 2,200 and 2,000 volts became the ordinary practice. In cases where the distance was very long, step-up transformers were used, as shown in Fig. 9. Here the current from the alternator *A* is first sent into the primary of the transformer *T*, which raises the voltage to any required amount, with, of course, a corresponding reduction in current. At the other end, the transformer *T'* steps down the high line pressure to whatever pressure is suitable for local distribution.

39. The single-phase system has been used in the past to a limited extent for the operation of synchronous motors. The ordinary single-phase synchronous motor will not start up even if it is not loaded and this is a great drawback to its use. The single-phase system is therefore seldom installed where power is to be transmitted for the operation

Single Phase Alternator

Fig. 8

Fig. 9

of alternating-current motors of large size. The motor *M* shown in Fig. 8 is the same in construction as an alternator, but it would have to be provided with some arrangement for bringing it up to speed. It is possible that in the future single-phase, alternating-current motors may be so improved that this system will be used much more largely for power purposes than it is now. Experiments have already been made in the operation of electric railways by means of single-phase motors constructed similar to series direct-current motors, but having laminated fields. The results obtained have been so satisfactory that a large increase in the use of single-phase current for power purposes may be expected, though at present the single-phase series motor has not been used to any great extent in regular commercial work.

TWO-PHASE POWER TRANSMISSION

40. The great advantage of the two-phase system over the single-phase is that it allows the operation of rotary-field induction motors and two-phase synchronous motors. Fig. 10 shows a two-phase system. In this case, we have taken the simplest arrangement, where the alternator feeds directly into the line without the use of step-up transformers. If, however, the distance is very long, step-up and step-down transformers could be connected in each phase, in a manner similar to that shown in Fig. 9. *A* is the alternator supplying the two currents differing in phase by 90° to the four line wires. *B*, *B* are two transformers supplying lights. One is connected on phase No. *1* and the other on phase No. *2*, so as not to unbalance the load on the alternator. *C*, *C* are two large transformers supplying alternating current at 389 volts to the rotary transformer *D*, which changes it to direct current at 550 volts suitable for operating the street-railway system *E*. *F*, *F* are two transformers supplying a two-phase induction motor *G*. *H* shows a two-phase synchronous motor. This is the same in construction as the generator *A*, and it is not necessary to use transformers with it, as it can be constructed for the same voltage as the generator.

Fig. 10

THREE-PHASE POWER TRANSMISSION

41. In the three-phase system, if the load on all three phases is kept nearly balanced, as it usually is in practice, only three wires are needed. For the same amount of power, line loss, and distance of transmission, the three-phase system requires only three-fourths the amount of copper called for by the single-phase or two-phase systems. For this reason, it is often used for the transmission itself, even if the power is generated by means of two-phase alternators. By a special arrangement of transformers, described later, two currents differing in phase by 90° can be transformed into three differing in phase by 120°. Fig. 11 is similar to Fig. 10, except that it is arranged for a three-phase transmission. There is little choice between the two-phase and three-phase systems so far as actual operation is concerned, the chief point in favor of the three-phase system being the saving in line wire.

42. In many large transmission systems, it is customary to generate the power in one large central station and distribute it at high pressure to a number of substations located at the various distributing centers. At these substations the current is transformed down and passed through rotary converters, if direct current is necessary, and distributed to the various devices to be operated. This is commonly done in connection with both lighting and street-railway work. If alternating current alone is used, the voltage is merely stepped down by means of large transformers.

At present, the three-phase system is the one most largely used for power transmission purposes. When the power is used for railway operation, the alternating current is changed into direct current, because heretofore alternating-current motors have not proved as satisfactory as direct-current motors for railway operation, hoisting, or other variable speed work. However, recent developments in the line of the single-phase series motor with laminated field seem to indicate that motors of this or similar type can be built so as

Fig. 11

to have sufficiently large output and at the same time run without sparking. These motors have properties much the same as series-wound, direct-current motors. They give a good starting torque and are well adapted to variable speed. A great deal of experimenting is at present being done with them, and it is probable that the single-phase system will, in the future, be a strong competitor of the two-phase and three-phase systems for railway work.

LINE CALCULATIONS FOR ALTERNATING CURRENT

43. The factors that determine the size of line wire for a direct-current transmission apply also, in a general way, to alternating-current systems. The resistance of the line causes a drop in pressure between the station and the distant end, and the line must be proportioned so that this drop will not be excessive. If the load to be carried is practically non-inductive, and if the distances are not long, the same rules that have already been given for direct-current circuits may be applied with sufficient accuracy to alternating-current lines. If, however, the lines are long, say more than 2 or 3 miles, there are other effects that must be taken into account. It must be remembered that the current is continually changing, and this introduces effects not met with in continuous-current circuits where the current flows steadily in one direction. The size of wire required will depend not only on the amount of the load, but also on the kind of load, i. e., on whether it consists wholly of motors or lights, or a combination of the two. In direct-current circuits, it makes no difference, so far as the drop in the line is concerned, how far the wires are strung apart on the poles, but in an alternating-current circuit this may have an appreciable effect.

The effects of self-induction and capacity on alternating-current transmission lines have already been given in connection with the subject of alternating currents. On all but very long transmission lines the effects of capacity are not serious, but the inductance of the line may have quite a large

influence on the line drop. The relation between the line drop, terminal E. M. F., and generator E. M. F. has been shown by means of an E. M. F. diagram, and by laying out such a diagram, the size of wire for any particular case could be obtained. For ordinary line calculations, however, it is convenient to use formulas that may be easily applied, and that will give results accurate enough for most practical purposes.

FORMULAS FOR LINE CALCULATIONS

44. Estimation of Cross-Section of Lines.—In a direct-current transmission line a certain drop in voltage is equivalent to a corresponding loss in power. With alternating current, the percentage drop in pressure may be quite different from the percentage loss in power. In case alternating current is used, the drop in voltage will very likely be more than the corresponding loss in power, because of the self-induction of the line. Just what the drop will be, corresponding to a given loss in power, depends on the size of the wire, distance apart on the poles, etc. The exact calculation of line wires for alternating current is a complicated matter, but in nearly all the cases that arise in practice they can be estimated with sufficient accuracy by means of comparatively simple formulas. The following formulas, originated by Mr. E. J. Berg, will be found convenient for estimating alternating-current lines. The different quantities entering into the calculations are as follows:

D = distance in feet over which power is transmitted (this distance is to be taken one way only, i. e., it is the single distance);

W_2 = total watts delivered at the end of the line (this number must express the actual watts delivered, not the apparent watts);

P = percentage of power lost in line (it should be noted that this percentage is that of the power delivered, not the power generated; also, it is the percentage power lost, not the percentage drop in voltage);

E_2 = voltage required at the receiving end of the line, i. e., the voltage at the end where the power is delivered;

t = a constant having the following values:

2,400 for a single-phase system operating lights only;

3,000 for a single-phase system operating motors and lights;

3,380 for a single-phase system operating motors only;

1,200 for a three-wire, three-phase and four-wire, two-phase system, all lights;

1,500 for a three-wire, three-phase and four-wire, two-phase system, motors and lights;

1,690 for a three-wire, three-phase and four-wire, two-phase system, all motors.

The cross-section of the wire required for any given case may then be calculated from the following formula:

$$\text{circular mils} = \frac{DW_2 t}{PE_2^2} \qquad \textbf{(11)}$$

EXAMPLE.— 300 horsepower is to be transmitted by means of the three-phase system over a distance of 5 miles with a loss of 10 per cent. of the power delivered. The pressure at the end of the line is to be 4,000 volts and the power is to be used altogether for operating motors. Calculate the size of line wire required.

SOLUTION.—In this case the distance D is $5{,}280 \times 5 = 26{,}400$ ft. The watts delivered will be $300 \times 746 = 223{,}800$. $P = 10$ and $E_2 = 4{,}000$. The constant t for this case will be 1,690; hence, we have from formula

$$\text{circular mils} = \frac{26{,}400 \times 223{,}800 \times 1{,}690}{10 \times 4{,}000 \times 4{,}000} = 62{,}407,$$

or about a No. 2 B. & S. Ans.

45. Estimation of Current in Lines.—The current in the line wires of an ordinary direct-current line is easily obtained by dividing the watts delivered by the voltage at the end of the line. The current in the case of alternating-current systems can be calculated by using a similar formula and multiplying by a constant, to allow for the circumstances under which the current is used, as follows:

$$\text{current in line} = \frac{W_2 T}{E_2} \qquad \textbf{(12)}$$

where W_s = watts delivered;

E_s = voltage at the receiving end of the line;

T = constant referred to above.

VALUES OF CONSTANT T

Single-phase system, all lights	1.052
Single-phase system, motors and lights	1.176
Single-phase system, all motors	1.250
Two-phase, four-wire system, all lights	.526
Two-phase, four-wire system, motors and lights	.588
Two-phase, four-wire system, all motors	.625
Three-phase system, all lights	.607
Three-phase system, motors and lights	.679
Three-phase system, all motors	.725

EXAMPLE 1.— 100 kilowatts is delivered by means of the two-phase, four-wire system to a mixed load of motors and lights. The pressure at the receiving end of the line is 2,000 volts. Calculate the current in each line wire.

SOLUTION.— 100 K. W. = 100,000 watts. For this case the constant T will be .588; hence,

$$\text{current} = \frac{100{,}000 \times .588}{2{,}000} = 29.4 \text{ amperes. Ans.}$$

EXAMPLE 2.— 200 kilowatts is transmitted by means of the three-phase system, the voltage between lines at the receiving end being 4,000 volts. The load consists wholly of motors; calculate the current in each line.

SOLUTION.— 200 K. W. = 200,000 watts. For this case the value of T will be .725; hence,

$$\text{current} = \frac{200{,}000 \times .725}{4{,}000} = 36.25 \text{ amperes. Ans.}$$

46. Estimation of Drop.—The volts drop in the line for a continuous-current system would be $\frac{P E_s}{100}$, when P is the percentage of delivered power lost and E_s is the voltage at the receiving end of the line. This formula can be made to give the approximate drop in an alternating-current line by multiplying it by a constant that takes into account the conditions under which the line is operated, as follows:

$$\text{volts drop in line} = \frac{P E_s M}{100} \qquad (13)$$

The value of M depends on the frequency, the power factor of the load, and the size of the line wire; its value, under various conditions, is given in the following table:

TABLE II

No. of Wire B. & S. Gauge	Area, Circular Mils	Values of M								
		30 Cycles			60 Cycles			125 Cycles		
		Lights Only	Motors and Lights	Motors Only	Lights Only	Motors and Lights	Motors Only	Lights Only	Motors and Lights	Motors Only
0000	211,600	1.26	1.27	1.24	1.64	1.85	1.85	2.44	3.06	3.14
000	167,805	1.20	1.17	1.14	1.49	1.63	1.62	2.15	2.62	2.67
00	133,079	1.15	1.08	1.05	1.39	1.46	1.42	1.92	2.25	2.29
0	105,535	1.10	1.00	1.00	1.30	1.32	1.28	1.73	1.96	1.99
1	83,694	1.06	1.00	1.00	1.23	1.21	1.16	1.57	1.74	1.73
2	66,373	1.03	1.00	1.00	1.16	1.11	1.06	1.44	1.54	1.53
3	52,634	1.02	1.00	1.00	1.11	1.04	1.00	1.35	1.38	1.38
4	41,742	1.00	1.00	1.00	1.07	1.00	1.00	1.26	1.26	1.22
5	33,102	1.00	1.00	1.00	1.04	1.00	1.00	1.19	1.16	1.11
6	26,251	1.00	1.00	1.00	1.02	1.00	1.00	1.14	1.08	1.03
7	20,816	1.00	1.00	1.00	1.00	1.00	1.00	1.09	1.01	1.00
8	16,509	1.00	1.00	1.00	1.00	1.00	1.00	1.06	1.00	1.00

EXAMPLE.— 600 kilowatts is to be transmitted a distance of 6 miles by means of the three-phase 60-cycle system. The loss in the line is to be limited to 10 per cent. of the power delivered, and the pressure at the receiving end of the line is to be 6,000 volts. The current is to be supplied to a mixed load of motors and lights. Calculate: (*a*) the size of the line wire; (*b*) the current in each line; (*c*) the volts drop in the line; and (*d*) the pressure generated by the dynamos at full load.

SOLUTION.—(*a*) 600 K. W. = 600,000 watts. 6 mi. = 6 × 5,280 = 31,680 ft. Using formula **11**, we have, since t for this case is 1,500,

$$\text{circular mils} = \frac{31,680 \times 600,000 \times 1,500}{10 \times 6,000 \times 6,000} = 79,200$$

A No. 1 B. & S. wire would therefore be used. Ans.

(*b*) In order to obtain the current in each line we use formula **12**, and for this case, the value of T will be .679; hence,

$$\text{current} = \frac{600{,}000 \times .679}{6{,}000} = 67.9 \text{ amperes. Ans.}$$

(*c*) In order to calculate the volts drop in the line, we use formula **13**. For a No. 1 wire and a frequency of 60 cycles on a combined lamp and motor load, the value of the constant M is found to be 1.21 by referring to the table; hence,

$$\text{volts drop} = \frac{10 \times 6{,}000 \times 1.21}{100} = 726. \text{ Ans.}$$

(*d*) Since the drop in the line is 726 volts, the pressure at the dynamo must be 6,000 + 726 = 6,726 volts when the full-load current is being delivered. Ans.

NOTE.—In the above example, the drop in the line would have been only 600 volts if continuous current were used.

EXAMPLES FOR PRACTICE

1. 250 horsepower is to be supplied to 60-cycle induction motors by means of the two-phase, four-wire system over a line 3 miles long. The pressure at the distant end of the line is to be 4,000 volts and the loss in the line is to be limited to 8 per cent. of the power delivered. Calculate: (*a*) the size of the wire required; (*b*) the current in each line wire; (*c*) the drop in the line.

Ans. { (*a*) 39,000 cir. mils, nearly; about No. 4 B. & S.
(*b*) 29.14 amperes
(*c*) 320 volts

2. A three-phase alternator delivers 400 horsepower to a mixed load of motors and lights. The pressure at the distant end of the line is 3,000 volts. Calculate the current in each line. Ans. 67.54 amperes

3. 5,000 incandescent lamps are supplied with current from a single-phase alternator, having a frequency of 125, over a distance of 3 miles. The loss in the line is to be limited to 10 per cent. of the power delivered, and the pressure at the end of the line is to be 3,000 volts. Allow 60 watts for each lamp supplied and calculate: (*a*) the size of the line wire; (*b*) the current in the line; (*c*) the volts drop in the line; (*d*) the voltage at the generator.

Ans. { (*a*) 126,720 cir. mils, or about No. 00 B. & S.
(*b*) 105.2 amperes
(*c*) 576 volts
(*d*) 3,576 volts

THE SELECTION OF A SYSTEM

47. From the foregoing it is seen that the engineer has a large number of systems to choose from when installing a given plant, and the selection of a system for any given case is a matter that requires careful consideration. We will, therefore, endeavor to sum up the principal advantages and disadvantages of the different systems as an aid in determining the system to be used in any given case.

The selection of a system, so far as its bearing on the location of the station is concerned, is comparatively unimportant in ordinary street-railway work, as the 500-volt, direct-current system is the standard American practice, due allowance being made for distance. But in the case of lighting and power distribution over large districts, and for long-distance railway work, the problems require careful analysis.

DIRECT-CURRENT SYSTEMS

48. If lighting and motive power are required, the first points to be considered are the characteristics of the town and nature of the business to be expected. In compactly built, thickly settled places, where a good site for a station can be had within a mile from the most distant lights or motors, there is no better or cheaper system, either in first cost, economy, or convenience of operation than the **direct-current system**, and whether it should be two- or three-wire, circumstances will determine. Where distances exceed 1 mile, boosters can be used advantageously, or the double-bus system of high and low potential. These last two arrangements are described more in detail later. In the following we will state the potential on the system of distribution, and due allowance must be made for drop in E. M. F. between generators and the point where the energy is utilized.

49. The **two-wire, 220-volt system** is in successful operation, and the 220-volt incandescent lamp is perfected for use on a commercial basis. There can be no question of the great advantage of a 220-volt, two-wire system over the three-wire system in simplicity and reduced cost of copper. It must be recognized, however, that greater care is required in insulating and installing all interior fittings that require more or less handling.

50. Three-Wire, 220-Volt System.—The advantages of the three-wire, 220-volt, direct-current system are many, among which may be mentioned the following; some of these also apply to the 220-volt, two-wire system.

1. Low potentials in dynamos, station apparatus, and street lines, and consequent perfect safety to the dynamo attendants, linemen, and the public.

2. Greatly lessened leakage, and therefore reduced risk from fire.

3. Convenience, cheapness, and ease of connection to the wiring on the consumers' premises.

4. The reading at the station, of pressure returned from extreme feeder ends by means of pressure wires, as described later, indicates quite accurately the pressure at the consumers' premises.

5. As the dynamos are run in parallel on the system in conjunction with station methods of regulation and control, it is possible to tie the mains and feeders together wherever convenient, thus insuring by equalization a more uniform pressure, no matter to what extent the electrical center or heavy load in the district may shift during the 24 hours. By enabling the lightly loaded lines to supplement those that are heavily loaded, this system of intermeshing conductors equalizes the potential and gives the best results from a given weight of copper.

6. The use of direct current makes possible the employment of storage batteries as an adjunct to the central station, thus lessening the hours during which it may be necessary to operate a considerable portion of the steam plant, minimizing

the labor account, and enabling one to run the boilers, engines, and dynamos at a higher efficiency during the period they are in operation, and to shut them down as soon as the load is low enough to justify throwing all or a portion of it on the storage battery. Moreover, in case of a sudden or heavy demand for extra current, such as may be occasioned by bad weather or sudden thunder storm, the battery is always on hand, ready to be thrown on instantly to supplement the dynamos, whereas it requires some time to start an idle engine and throw in its dynamos.

7. Electrolytic and electroplating work can be done with the direct current, but is impossible with alternating currents, except at considerable expense and complication for rotary converters or other transforming devices.

8. The measurement of power, calculation of conductors, and arrangement of circuits are simpler than in the alternating system, on account of the absence of induction and consequent lag effects.

9. Simple and efficient motors are readily installed and operated, and form a considerable source of income.

10. The broad establishment of the business, the vast amount already served by the three-wire system, and its standardized methods largely influence its adoption.

But the three-wire system has manifest disadvantages, the most prominent of which are as follows:

1. The two sides of the system must be kept at nearly equal loads, as want of balance occasions a difference in potential between the positive and negative sides, and consequently a difference in the brilliancy of the lights.

2. If overhead lines are used for large currents, they are cumbersome, costly, and extremely liable to disaster from high winds or lightning.

3. It is impossible to cover a very large extent of territory at 250 volts potential without great expense for copper.

4. A ground on any part of the wiring, no matter how trifling in itself, may be a fault on the whole system, and if not promptly eliminated may give rise to a bad short circuit.

5. Switchboard and other connections are complicated because of the use of three wires and the operation of the dynamos in pairs connected two in series.

51. Three-Wire, 500-Volt System.—A larger extent of territory can be served by the use of the three-wire, 250–500-volt, direct-current system because it has greater capabilities of expansion, with less investment in copper for lightly loaded or scattered territory, as well as requiring less copper in heavily loaded business districts. The advantage stated for the 500-volt, three-wire system with the same current distribution and the same station location, is that it will cover, at the same cost of copper, a territory four times as large as with a 250-volt, three-wire system. Increased risks are encountered as mentioned, as regards insulation within buildings and for underground distributing systems because of higher potential, but these conditions are successfully met by the employment of standard appliances. The important point is that the ignorant consumer shall be fully protected when current is supplied him at potentials bordering on the danger line.

ALTERNATING-CURRENT SYSTEMS

52. The **alternating-current system** has great value in the special field of transmission for long-distance and house-to-house supply in scattered territories, and is excellent and comparatively economical as a temporary expedient for developing business in a new territory. Before alternating current can be used in compact territory in combination with, or to replace, direct current, the following improvements are necessary:

1. A type of motor must be developed that will meet all commercial requirements, which can be used successfully for all classes of business without causing disturbance of the fixed potential of the system.
2. A universal system of supply that does not require transformers or anything except a meter to be located on the premises of the customer.

3. Some type of apparatus that will replace the storage battery as used in connection with direct current.

Alternating current cannot be used in connection with storage batteries, except through the employment of a rotary converter or motor generator for charging the battery. The use of such converting apparatus will be justified when the amount of current supplied and compensation received is sufficiently large to overbalance the extra cost for special equipment and the losses incurred for conversion of energy.

The direct-current motor can be better applied for general power work, and in some respects is superior to the alternating-current motor in its electrical operation. The disturbing effects on the system are less, when starting and stopping large motors. The initial cost of direct-current motors and their few necessary auxiliaries is much less than that of alternating-current motors. Alternating-current induction motors, on the other hand, have the advantage over direct-current of not requiring a commutator and brushes. Direct current is best adapted for elevator work.

With direct current at least 80 per cent. of the manufactured power can be accounted for through the meters on a good system, whereas with the alternating-current system, from 50 per cent. to 60 per cent. only of the power can be accounted for; the rest is lost in transformers and special devices.

The comparative usefulness of the two systems for commercial distribution is illustrated in Chicago, where with a maximum output of 25,000 kilowatts, 20.4 per cent. is for 60-cycle distribution covering a territory of 58 square miles, and 79.5 per cent. is for direct-current distribution over a territory of 10 square miles.

The concensus of expert opinion is that the alternating-current system has not attained the requisite degree of perfection for general distribution, in compact territory, though for long-distance work it is indispensable. In compact territory it cannot be used with storage batteries; the motor cannot be used for general power purposes. It is therefore

evident that there is not yet any single ideal system that can be universally applied to serve all local conditions; special requirements, the environment of the station, and relative commercial importance of the various classes of service must be taken into account in determining what is most desirable for each given locality.

53. The problem for a combination system may, for example, be solved as follows:

For incandescent lighting and motive power in the business and near-by residential districts, the three-wire, direct-current system, 220 volts.

For incandescent lighting and some classes of motive power in scattered and long-distance territory, the alternating-current system, 2,300 volts primary; 110 to 220 volts secondary.

For arc lighting in streets, the enclosed series-arcs on the alternating-current system.

If the bulk of the power is transmitted over a long distance, or supplied to a widely scattered area, the two-phase or three-phase systems would be installed; that is, only one kind of current would be furnished from the station, and if direct current were essential for any special purpose, it would be transformed at the consumers' premises by means of a rotary converter.

In general, it is well to avoid too great a variety of apparatus in a station, because it necessitates several sets of duplicate machines. Considerations of economy are frequently sacrificed in order to make the generating units in a given station uniform as to size and output.

FREQUENCY

54. The choice of a proper **frequency** in alternating-current systems is important. The early single-phase plants were designed for from 125 to 150 cycles, and some polyphase machines have been built for these frequencies. The high inductive effects, troubles in parallel operation, and the

difficulty of obtaining low speeds have caused such high frequencies to be abandoned in favor of 60 cycles or less. In polyphase plants, therefore, 60, 40, and 25 cycles have come to be the standard frequencies. The choice of frequency should be governed by a careful consideration of the apparatus to which the plant is to furnish power.

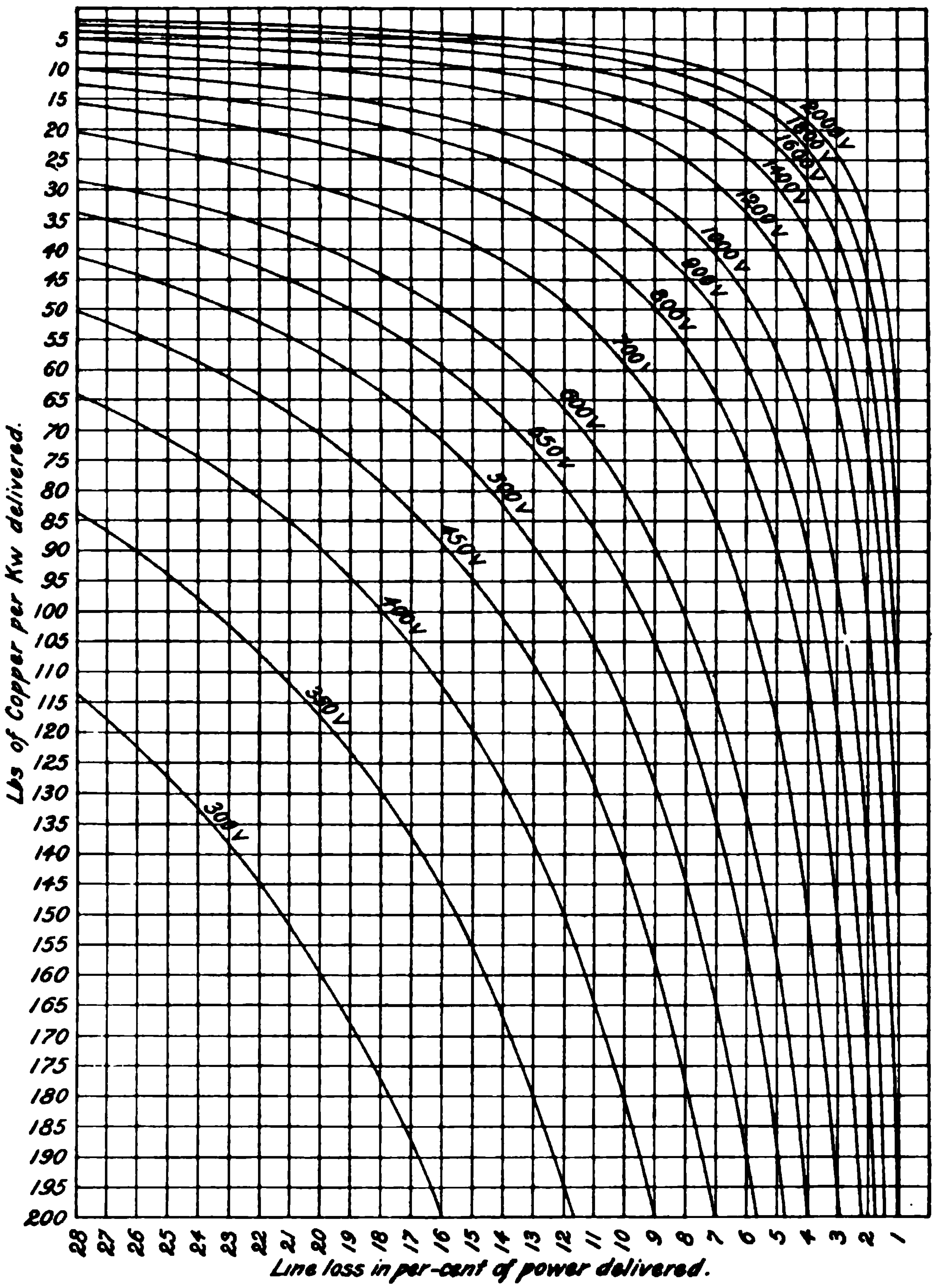
If the alternating current is to be used for lighting purposes only, a high frequency affords the advantage of low first cost, and such a system might be even single phase. However, the demand for electric power is now so great that a low-frequency polyphase system is nearly always used in modern alternating-current installations. The cost of transformers, per kilowatt, diminishes as the frequency increases and this is one of the reasons why high frequency was used in the early installations when belt-driven, high-speed alternators were used almost exclusively. With the introduction of slow-speed, direct-driven machines, low frequencies became desirable, and the increasing use of induction motors, synchronous motors, and rotary converters also led to the introduction of lower frequencies. A frequency of 60 cycles is suitable for incandescent lighting, arc lighting, and some motive power. When the current is used nearly altogether for power purposes, it is better to use lower frequency; 60 cycles will only be found satisfactory with synchronous motors, rotary converters, and similar apparatus when the speed regulation of the motive power is very good, because of the hunting or periodic surgings in speed that are liable to occur. A frequency of 40 cycles permits current for both lighting and power purposes to be supplied to advantage. It is within the limit of reasonable safety for operating rotary converters and is the lowest limit for satisfactory working of incandescent and arc lights; 40-cycle equipments are not in general use and should only be adopted after analyzing all anticipated or existing conditions and finding that 60 cycles cannot be used with reasonable safety. A frequency of 25 cycles is very commonly used where the current is supplied wholly for power purposes.

COST OF CONDUCTORS

55. In order to determine the best potential for a power transmission, it is necessary to consider carefully the cost of the transmission circuit. The weight of the electric conductor decreases as the square of the potential employed, and increases as the square of the distance. Dividing the potential by the distance gives a convenient figure, which can be used for all potentials and distances. The curves on the diagram, Fig. 12, given by the General Electric Company, furnish a ready means of obtaining the amount of copper required for a given power transmission. The figures on the curves indicate volts per mile; i. e., potential of line at generator divided by distance in miles. The weight of copper, potential, and line loss are in terms of the power delivered at the end of the line, and not of generated power. The curves are correct only for three-phase current with 100 per cent. power factor. Two-phase, single-phase, or continuous-current transmission requires one-third more copper. Five per cent. has been allowed for sag and waste in weights of copper given.

EXAMPLE.—If copper is worth 15 cents per pound, what will the cost of copper be for a line (three-phase) to transmit 1,000 kilowatts at 10,000 volts over a line 10 miles long, with a loss of 5 per cent. of the delivered power?

SOLUTION.—Since 1,000 K. W. at 10,000 volts is to be delivered over a line 10 mi. long with 5 per cent. loss, we have $\frac{10{,}000 \text{ volts}}{10 \text{ mi.}}$ = 1,000 volts per mi. Looking on the 1,000-volt curve, we find 5 per cent. loss corresponds to 57 lb. of copper per kilowatt delivered. 1,000 K. W. $\times$ 57 = 57,000. If copper costs 15c. a pound the cost will be 57,000 $\times$ \$0.15 = \$8,550. Ans.



Lbs of Copper per Kw delivered.
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
185
190
195
200
2000 V
1800 V
1600 V
1400 V
1200 V
1000 V
900 V
800 V
700 V
600 V
450 V
500 V
450 V
400 V
350 V
300 V
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
Line loss in per-cent of power delivered.

FIG. 12

COMBINED OPERATION OF DIRECT-CURRENT DYNAMOS

OPERATION OF DYNAMOS IN SERIES

56. Dynamos are not very often run in series. Perhaps the most common case is where they are run in pairs of two in series on the three-wire system. Whenever dynamos are connected in series, their pressures are added in the same way as the voltage of two or more cells connected in series, but the current output is not increased. Series-wound dynamos are sometimes run in series, especially when used for arc lighting. In this case, the connections are very simple; the positive pole of one machine is connected with the negative pole of the other, so that the pressures of the two machines are added together instead of opposing each other. Generally speaking, series-wound, shunt-wound, or compound-wound machines may be run in series with very little difficulty; in the case of the last named type, the compound coils must of course be connected in series in the line. In most cases, however, the demand is for a large current output rather than for a high voltage; hence, plain series running is not common, except, perhaps, on arc-light circuits.

OPERATION OF DIRECT-CURRENT DYNAMOS IN PARALLEL

57. Dynamos, both direct and alternating, are much more frequently operated in parallel than in series. In Fig. 13 each machine generates the same voltage, and the pressure between the lines is the same as if a single machine were used; i. e., the pressure between the lines is not increased by adding machines in parallel, but the current delivered to the line is increased because the line current is the sum of the currents delivered by each of the machines.

Each machine is connected through its main switch *M*, *M'* to the heavy conductors *C*, *D*, like terminals of each machine being connected to the same bar. Each machine, when so connected, delivers current to the main **bus-bars** *C*, *D* and thence to the line.

It is not as easy a matter to operate machines in parallel as in series. It is evident that the voltage of each of the machines must be kept at the proper amount if the combination is to operate satisfactorily; for, suppose the E. M. F. of *B* should fall below that of *A*, then *A* would send current through *B* and run it as a motor, and *B* would thus be

FIG. 13

taking current from *A* instead of helping it feed into the line. There are a number of things that must be taken into account when machines are run in parallel that do not have to be considered when they are run separately. Compound-wound machines are run in parallel more than any other type in this country, though shunt machines are frequently run in this way also. Series machines are seldom run in parallel, for reasons to be given later. We will, however, first consider the series machine briefly, because the compound-wound machine is a combination of the series- and shunt-wound machines.

SERIES DYNAMOS IN PARALLEL

58. Suppose two series dynamos are in parallel, as shown in Fig. 14, and assume that they are delivering current to a load of some kind and that each machine supplies, say, one-half of the current. Now, if the E. M. F. of one of the machines *A* drops slightly, due to a slight variation in speed or any other cause, the amount of current delivered by *A* will decrease, and thus decrease the field excitation, because the current through the field coil is the same as the current delivered by *A*. This lowering of the field excitation of *A* will still further cut down its E. M. F. and matters will go from bad to worse until, in a very short time, *A* will be driven as a motor, unless the belt on the heavily loaded machine should slip and thus bring down its voltage. The trouble is

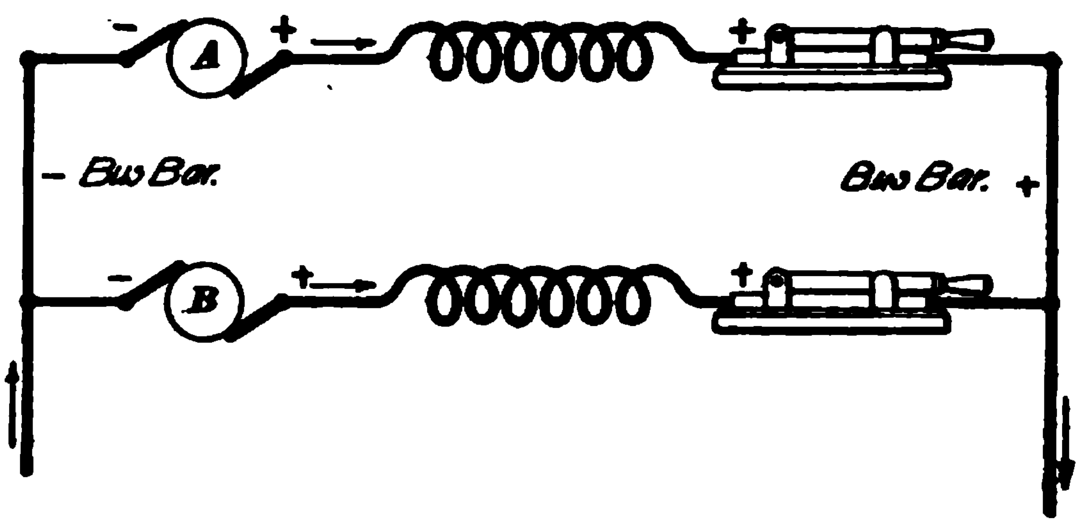


FIG. 14

made still worse by the fact that the extra load thrown on *B* will raise its E. M. F., because the field of *B* will be strengthened. Moreover, when *A* is run as a motor, its direction of rotation will be reversed; and this may result in considerable damage. It is thus seen that two series machines connected in parallel, as shown in Fig. 14, will be very unstable in their action, and it is not practicable to so operate them.

59. Equalizing Connection.—The unstable condition just referred to can be remedied by using an equalizing connection, or **equalizer**, as it is commonly called. This is shown in Fig. 15, where the wire *c d* is the equalizer. It is a wire of low resistance connecting the points *c* and *d*

where the series-coils are attached to the brushes; *e* and *f* are the regular terminals of the machine. Now suppose that the machine *B* delivers a greater current than *A*; part of this current will flow to the + line through the coil *df*, but part of it will also take the path *d–c–e* through the field coil *ce* of

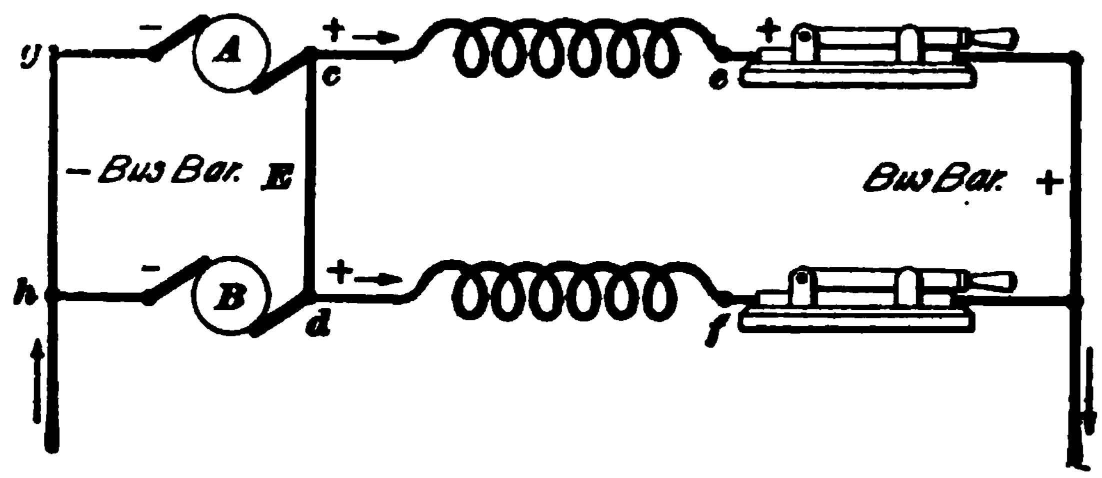


FIG. 15

machine *A*. The result is that part of the current delivered by *B* helps to keep up the field excitation of *A*, thus bringing up its voltage and equalizing the load between the machines. If *A* delivers the greater part of the load, due to a drop in the voltage of *B*, then part of the current flows through the path *c–d–f* and strengthens the field of *B*.

SHUNT DYNAMOS IN PARALLEL

60. Shunt dynamos will operate very well in parallel. They have two properties that make their parallel operation a comparatively easy matter. In the first place, they are capable of exciting their own field no matter whether they are delivering current to the main circuit or not. In the second place, their voltage drops slightly with an increase in the load, and this tends to make their parallel operation stable. Suppose two shunt machines are arranged as shown in Fig. 16; *A* and *B* are the armatures, *S*, *S′* the shunt field windings, and *r*, *r′* the adjustable field rheostats. *L*, *L′* are switches in the field circuit and *M*, *M′* main switches connecting the machines to the line. Suppose that machine *A* is in operation, as indicated by the closed position of switches *L* and *M*. To throw machine *B* in parallel, it is run up to speed and the switch *L′* closed; *B* will at once

begin to pick up its field and run up to voltage. If the two machines are generating the same voltage and if their polarity is the same, as it should be, a voltmeter connected to blocks *1*, *2* will give no deflection, because the tendency of the machine *A* to send current through the voltmeter will be opposed by *B*. This state of affairs can be brought about by adjusting the rheostat r' until the voltmeter indicates that the voltages of the machines are equal, after which the switch M' may be closed and the field excitation of *B* again adjusted until the proper share of the load is carried. In practice, it is generally found better to have the voltage of *B* about 1 or 2 per cent. higher than that of *A* when the machine is thrown in.

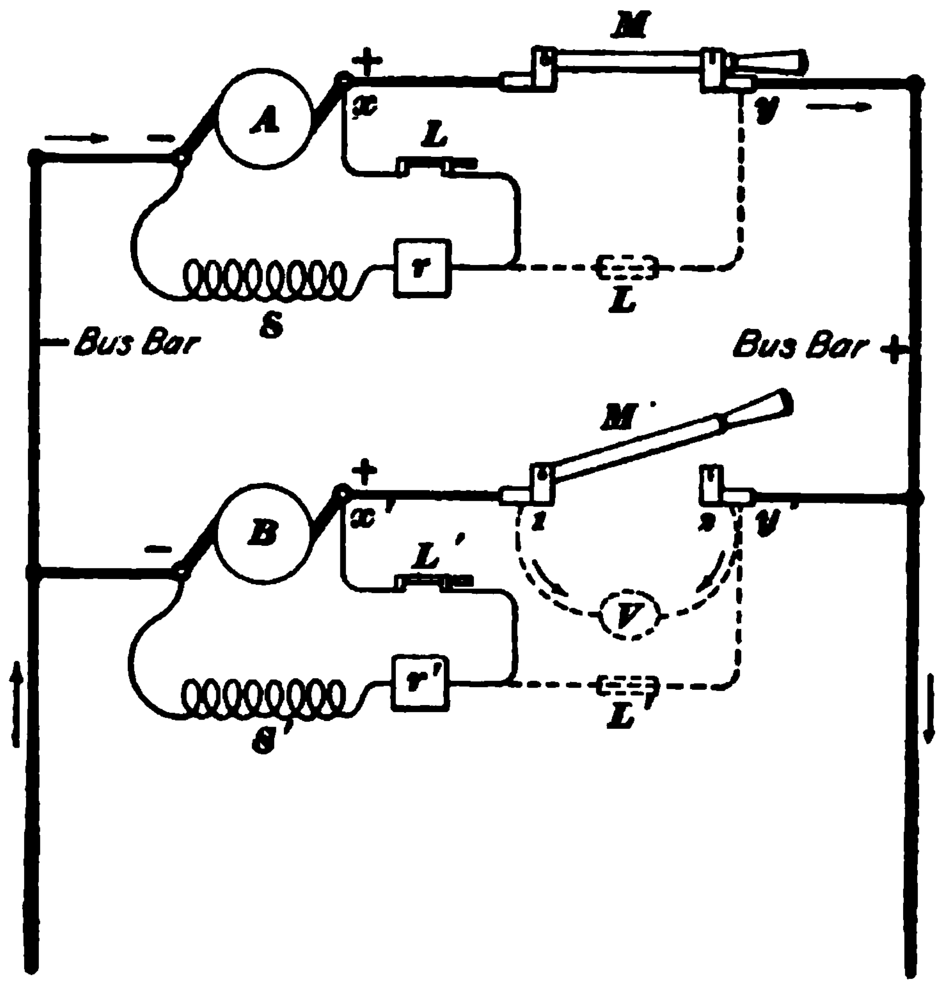


FIG. 16

Very often, when shunt machines are arranged for parallel operation, the field is connected across the bus-bars instead of the armature of each machine. When this is the case, the field connection is made as indicated by the dotted lines ry, $r'y'$, instead of being connected as shown by the full lines rx, $r'x'$. The effect of this is that the switch *M* must be closed before *A* will pick up, assuming that *B* is not in operation. If *A* is running and *B* is to be thrown in, then the switch L' is closed and *B*'s field is at once excited from the mains, so that *B* comes up to voltage almost immediately; after the voltage has been adjusted, switch M' may be thrown in as before.

61. We will suppose that the two shunt machines, Fig. 16, are running properly in multiple and will now see whether

their operation will be stable or not. It has already been seen that the shunt dynamo lowers its voltage as the current output increases. Now suppose that the voltage of *A* should drop slightly on account of a drop in speed or from any other cause. The tendency will be to throw the bulk of the load on *B*, with the result that *B*'s voltage will also drop on account of the above-mentioned property. The dropping of *B*'s voltage will relieve it of part of its load and will make it divide with *A*. It is thus seen that there is an automatic tendency for the load to equalize. Again, suppose that the load on the line is suddenly increased, and that machine *B* takes more than its share of the current; the large current delivered by *B* will cause its E. M. F. to drop to more nearly that of *A*, and the load will thus be equalized. If the voltage of one machine should for any reason become so low that the other machine runs it as a motor, no harm is liable to result, because the direction of rotation of the machine as a motor will be the same as when driven by the engine as a dynamo. As far as parallel running goes, the shunt dynamo is satisfactory, but it has been replaced by the compound machine, because the latter will maintain the line voltage with an increase of load; whereas, with shunt machines, the line voltage will fall off, unless the switchboard attendant cuts out some field resistance.

COMPOUND MACHINES IN PARALLEL

62. Since the compound machine is a combination of the series and shunt machines, one would naturally infer that the arrangement for parallel running would be a combination of the two preceding ones. Fig. 17 shows the connections in their simplest possible form; machines *A* and *B* are of equal size and the equalizer *E* runs directly between them; *c* and *f* are the + terminals of the machines, while *c d* and *f e* represent the leads, or cables, running to the switchboard; *g h* and *k l* are the negative leads running to the negative bus-bar *h l*. There would, in practice, be a main switch in each of these negative leads, but as they

are not essential for the present purpose they have been omitted. As shown by the full lines in Fig. 17, the shunt windings of the machines are connected in what is known as **short shunt**; i. e., the shunt field is connected across the brushes. Sometimes the shunt field is connected in **long shunt** across the terminals of the machine or across the bus-bars. It makes very little difference as to the performance of the machine which connection is used.

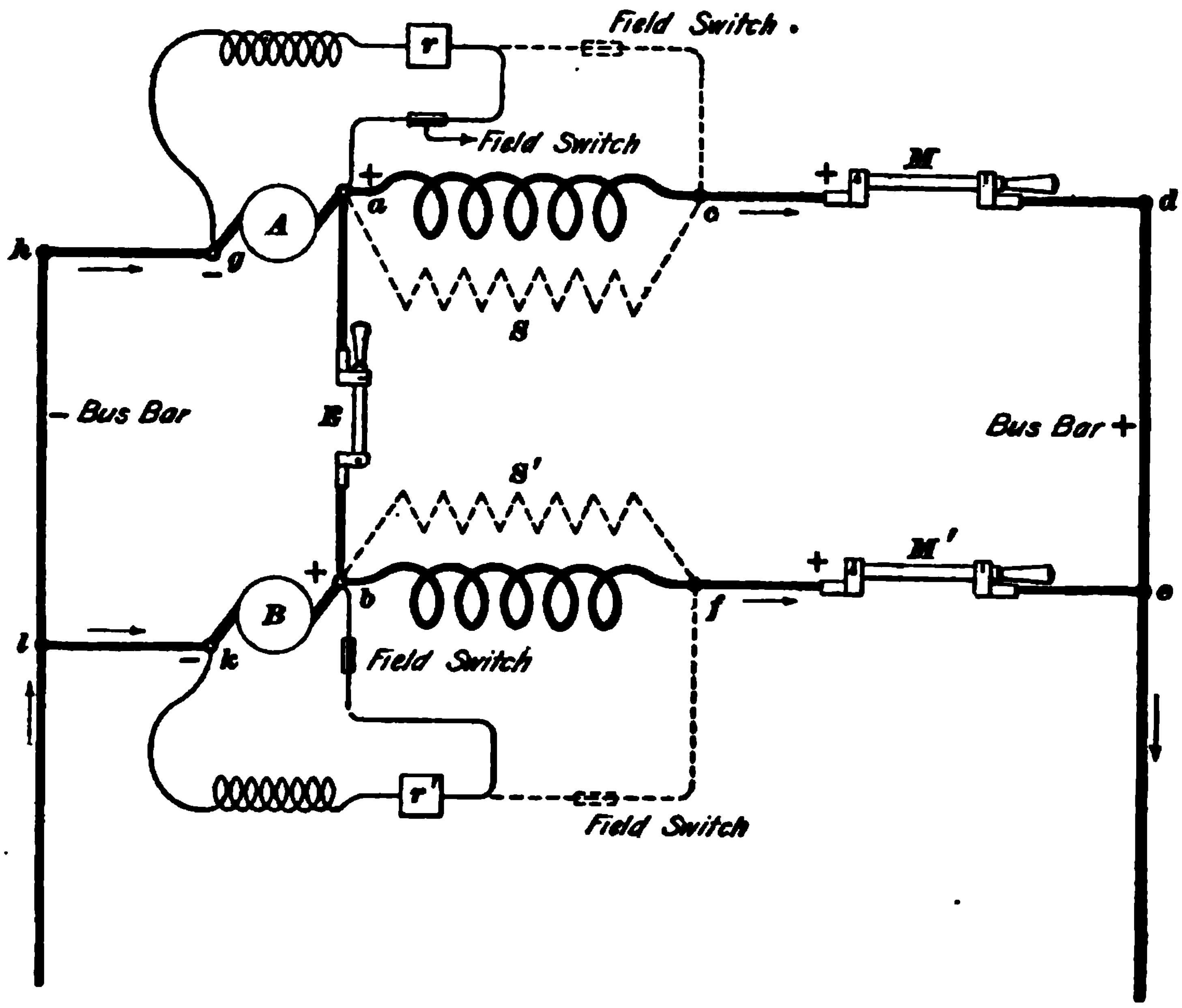


Fig. 17

Most compound machines are provided with low-resistance shunts S, S' across their series-coils in order that the degree of compounding may be adjusted. These shunts should be adjusted so that the machines, when running separately, will give the same degree of compounding, which means, in the present case, that when each machine is delivering the same current, the voltage generated will be the same, because we are now assuming that A and B are of equal

size. Another condition that must be fulfilled is that the resistance between the points *a* and *d* must be the same as between *b* and *e*. Since we are, for the present, assuming that the machines are of the same size and make, the resistance of their series-coils *a c* and *b f* will be almost exactly the same. The resistances of the switchboard leads *c d* and *f e* must, therefore, be equal; the resistance of the equalizer *E* should be as low as possible, and it should never be more than the leads *c d* or *f e*.

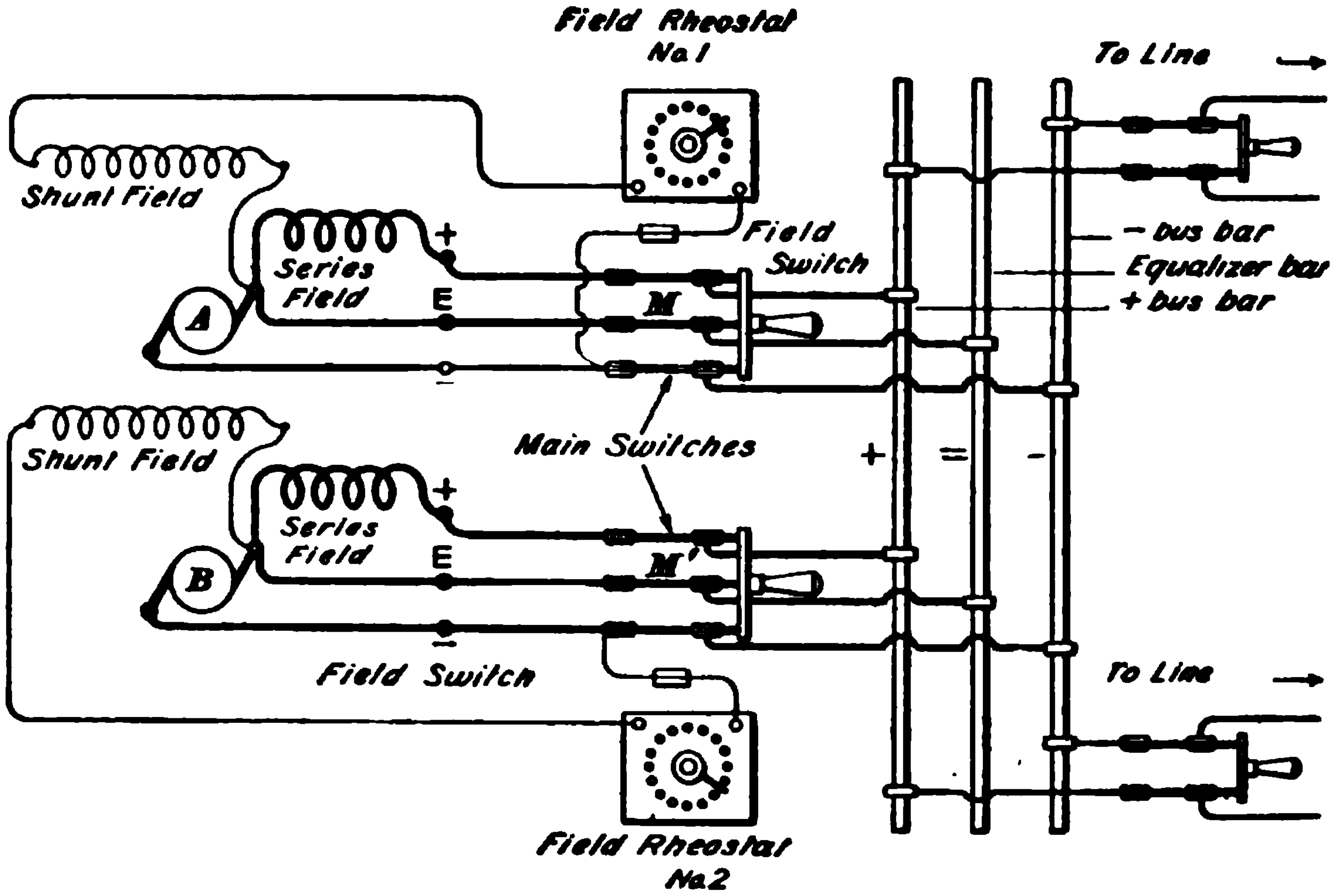


FIG. 18

63. We will now examine the action of the machines under a varying load. In the first place, if the resistance between *a d* is equal to that between *b e* and the machines are delivering equal currents, then the drop through *a d* will equal the drop through *b e* and points *a* and *b* will be at the same potential. Since current can only flow between points at different potentials, there will be no current in *E* under such circumstances. Suppose, however, that *A* delivers a greater current than *B*; then the drop in *a d* will exceed that in *b e* and current will flow through the path *a–E–b–f–M′–e* and thus build up the voltage of machine *B* and equalize the load. If *B* delivers more current than *A*, the drop in *b e*

exceeds that in $a\ d$ and current flows through the path b–E–a–c–M–d, builds up the voltage of A, and makes A take its share of the load.

64. In Fig. 17 the equalizer E is shown as connecting the positive brushes. This is usually the case in practice, though it would work just as well if both a and b were negative brushes and $c\ f$ the negative terminals of the machines. It is only necessary to see that the equalizer connects those brushes to which the series-coils are attached, and also to see that the brushes are of the same polarity on each of the

ra bar
/chboard

To c

Fig. 19

machines. In some cases, the equalizer wire is run directly between the machines as shown, but often a third wire is run from points a and b to the switchboard and there connected to an equalizer bar, as shown in Fig. 18. This represents a very common arrangement, triple-pole switches being used; the two outside blades for the + and – leads and the middle blade for the equalizer. There is a difference of opinion as to whether it is better to run the equalizer to the switchboard or run it directly between the machines, as in Fig. 17. The most recent practice tends toward running it directly and placing the equalizer switch near the machine.

This undoubtedly makes the connections shorter and thus leads to better regulation. In such cases, the equalizer switch is usually mounted on a pedestal near the machine, as shown in Fig. 19.

65. In some railway plants, especially in those where large generators are used, the main switch that is on the same side of the machine as the equalizer is placed on the stand near the machine alongside the equalizer switch. These two

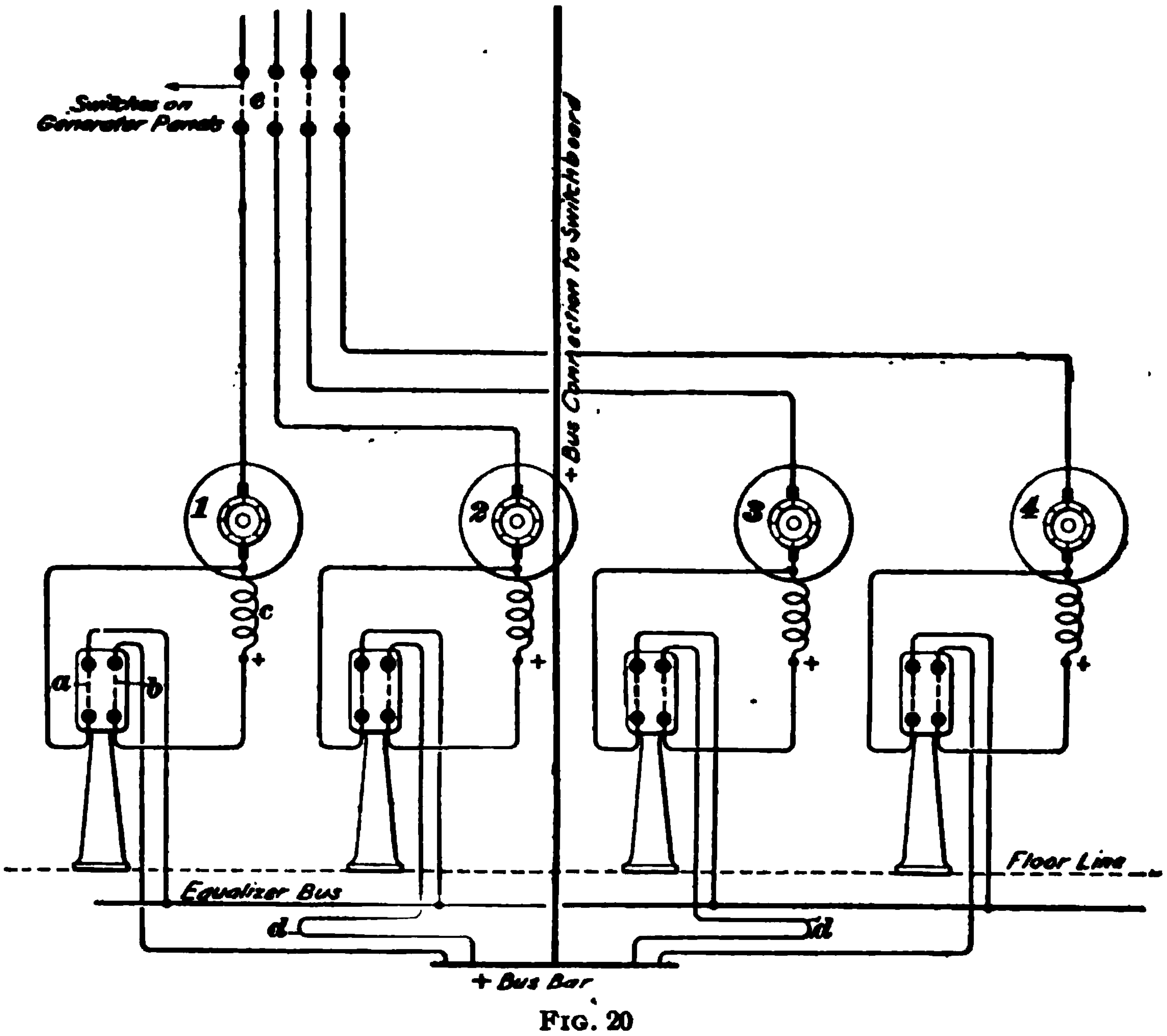


FIG. 20

switches are at practically the same potential, and there is no objection to placing them near each other. In case this is done, one of the bus-bars is placed under the floor near the machines and connected directly to the main switch. This shortens the connections considerably and makes the equalization of the load closer. It also has the advantage of simplifying the switchboard connections and avoiding crowding on the generator switchboard panels. Fig. 20

shows the arrangement referred to. For lighting switchboards or for small railway boards, both terminals of each machine are run to the switchboard. In Fig. 20 the main connections only have been shown, the shunt coils of the machines and all minor connections being omitted. The switches *a* and *b* are the equalizer and main + switches, respectively, the equalizer switch being connected to the brush to which the series-field *c* is attached. The + lead from *b* connects to the + bus-bar under the floor. Note that these leads should all be of the same length in order to secure close equalization. In the case of machines *1* and *2* the leads are doubled back as shown at *d* in order to make them of the same length as those running from the more distant machines.

The general method of starting up, say, machine *1* and throwing it in parallel with others is as follows: See that all switches on the generator panel of the machine are open, and get the dynamo up to speed. Then close the equalizer switch *a* and the + switch *b*. Also, close the field switch on the generator panel. Some of the current furnished by the other machines will flow through the series-coils *c*, because the series-coil of machine *1* is in parallel with the other series-coils. This current in the series-coils will cause the machine to *pick up* rapidly, and since the shunt circuit is also closed, the machine soon comes up to full voltage. The voltage is then adjusted by means of the rheostat until it is equal to or a little higher than that of the other machines, and the negative switch *e* is then closed, thus placing the machine in parallel with the others. This method of procedure applies to the case where the +, −, and equalizer switches are independent of each other, as is usually the case in modern installations. When triple-pole switches are used, as in Fig. 18, all three must of course be closed together after the machine has been allowed to pick up its field and has had its voltage adjusted. After the machine has been thrown in parallel, its load is adjusted by varying the field excitation. In case the machine is provided with a circuit-breaker, as is nearly always the case on modern switchboards, the circuit-breaker should be closed before the

main switch. If any rush of current then occurs when the main switch is closed, the circuit-breaker is free to act and disconnect the machine.

66. Main and Equalizer Cables.—In connecting the machines to the switchboard, cables of ample capacity should be used. For most cases it will be sufficient to allow from 1,200 to 1,500 circular mils per ampere. For very large currents it is advisable to use two or three cables in parallel rather than a single large cable, as better radiating facilities are thereby provided. The equalizer should be of the same size as the main cables. In some cases an allowance as low as 1,000 circular mils per ampere is made for these main cables, but the better practice is in favor of a more liberal cross-section.

67. So far, in all that has been said, the machines were supposed to be alike in size and general design. Under such circumstances, there is generally no great difficulty in getting compound machines to operate properly in parallel. Trouble is often experienced, however, when it comes to operating machines of different construction and size. Some field magnets will respond to changes in field excitation much more quickly than others, and other differences in design may have considerable effect on the performance of the machines when they are run in parallel. With two machines of different size, the problem is to get the load to divide between them in proportion to their size. For example, suppose a large machine A is connected in parallel with a smaller machine B, as shown in Fig 21. Each is supposed to be adjusted so that it gives the same degree of compounding when operated by itself. Also, when each machine is delivering its proper share of the load, the drop between $a\,b$ must equal the drop between $c\,d$. For example, if I is the full-load current of A, R the resistance between a and b, I' the full-load current of B, and R' the resistance between c and d, then $I R$ must equal $I' R'$. Now, the resistance of the series-coils cannot very well be altered in order to bring about the required condition of affairs, so that the only remedy is to insert resistance of

some kind in the leads *e b* or *f d* until the above drops become equal. This resistance will, of course, be very small and may be made up of a short piece of heavy German-silver strip or even an extra amount of cable in one of the leads. In the figure, it is indicated at x, though it may be necessary to insert it in the main lead of machine B. The resistance must be inserted in series with the machine giving the least drop between the points mentioned above. Many times the attempt is made to bring about the adjustment by changing

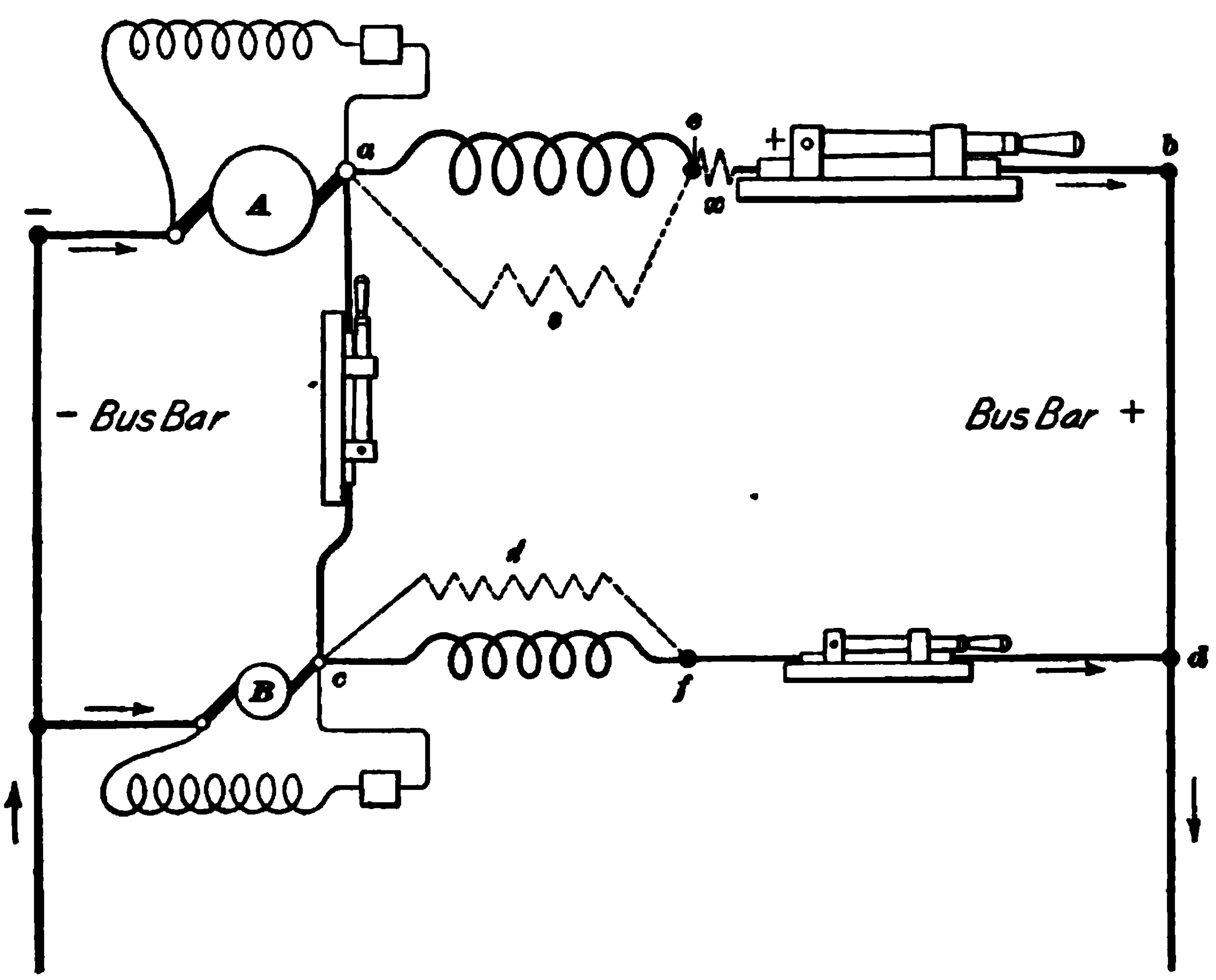


FIG. 21

the shunts s, s', but such attempts are useless, because just as soon as the machines are put in parallel, s and s' are also in parallel and are practically equivalent to one large shunt across the fields of both machines. The consequence is that any change in the shunts affects both machines. The adjustment must, therefore, be made in the main lead between the series-coil and the bus-bar, and any resistance so inserted must have the same carrying capacity as the series-coils. A change in the shunt across the series-coils will change the

compounding of the machines as a whole, but it will not better their condition as regards the correct division of the load.

68. Compound Machines in Parallel With Shunt Machines.—It is not practicable to run a compound machine in parallel with a shunt machine. If, for any reason, the compound machine takes a little more than its share of the load, the strengthening of its series-coils makes it still further overload itself, with the result that the field rheostat of the shunt machine calls for constant attention. The only way to run this combination satisfactorily is either to cut out the series-coils of the compound machine, thereby making both plain shunt machines, or else provide the shunt machine with compound coils.

COMBINED RUNNING OF ALTERNATORS

ALTERNATORS IN SERIES

69. Alternators cannot be run in series unless their armatures are rigidly connected by being mounted on the same shaft, so that the E. M. F.'s generated by the two machines will always preserve exactly the same relation with regard to each other. If the machines are driven separately, the E. M. F.'s may aid each other at one instant and oppose each other the next, thus making their operation unstable. There is, in any event, little occasion for operating alternators in series; the object of series operation is usually to obtain a high voltage, and this can readily be generated in a single alternator, or, if the alternator does not furnish a sufficiently high voltage, the pressure can easily be raised by means of transformers.

ALTERNATORS IN PARALLEL

70. Alternators can be operated in parallel, although they are, as a rule, more troublesome than direct-current machines. This is especially the case if they are very different in size and design. For example, alternators with the old-style, smooth-core armatures are hard to run in parallel

with modern machines having toothed armatures. In fact, in many of the older lighting stations special precautions were taken at the switchboard to see that two alternators should never be thrown in parallel.

71. Alternators are operated in parallel in much the same way as direct-current machines, so far as connections are concerned; i. e., they are usually connected to bus-bars through the intervening main switches. If the alternators are compound wound, equalizing connections should be used;

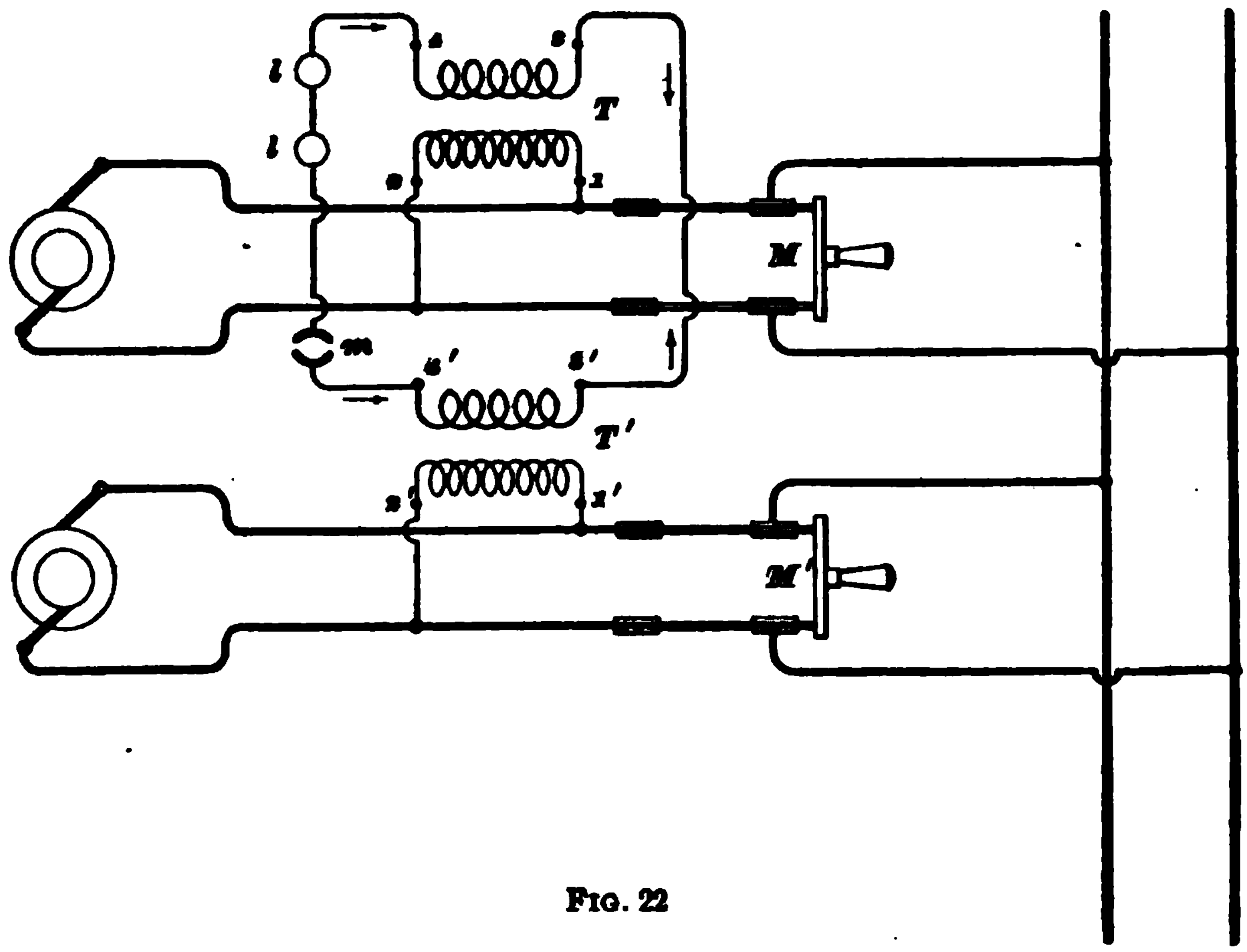


FIG. 22

but very many are operated with a separately excited field only and no equalizing connection is necessary, the whole scheme of connection corresponding more nearly to the running of shunt-wound machines in parallel.

Suppose two single-phase alternators *A* and *B* are connected in parallel. In order that the machines may operate properly and each take its proper share of the load, it is, of course, necessary to have their voltages equal or nearly so. There is another important condition that must also be fulfilled; the machines must be in **synchronism**. This

means that both machines must run at exactly the same frequency, for if this were not the case, they would get out of step. Before two alternators are thrown in parallel, equality of frequency is the most important condition to be fulfilled. A slight difference in phase will cause an exchange of current between the machines, but they will pull each other into phase if the frequencies are equal.

72. Synchronizing.—The state of synchronism may be ascertained by means of **synchronizing lamps** connected as shown in Fig. 22. *T*, *T'* are two small transformers having their primary coils connected to the alternators, as shown. It should be noted that similar terminals *1*, *1'* are connected to similar sides of the machines. The secondaries are connected in series through a pair of lamps *l*, *l* and a plug switch *m*. If the machines are exactly in phase, terminals *3* and *3'* will have the same polarity at the same instant and the polarities of *4* and *4'* will also be alike. But since like terminals are connected together, the two secondary voltages will just neutralize each other, as indicated by the arrows, and the lamps will not glow. If the machines were directly opposite in phase, the lamps would light up to full candlepower. It is evident that by reversing the connections of one of the transformers the state of synchronism will be indicated by the lamps being bright. When machine *B* is started and the plug inserted at *m*, the lamps rapidly fluctuate in brightness; but as *B* comes more nearly in synchronism the fluctuations become much slower. When they have become as slow as one in 2 or 3 seconds, the main switch *M'* is thrown in at the middle of one of the beats when the lamps are dark. In some cases, the connections are so made that the lamps are bright when synchronism is attained. Whether the state of synchronism will be indicated by light or dark lamps depends simply on whether the transformer secondaries are connected so as to assist or to oppose each other.

73. Synchronizing Two-Phase and Three-Phase Machines.—Fig. 22 shows the synchronizing arrangement for a single-phase machine. For a two-phase or three-phase

machine the same arrangement may be used, but care must be taken to make sure that the transformers T, T' are connected to corresponding phases on each of the machines. This may be determined by using two pairs of transformers; i. e., one regular pair, as in Fig. 22, and a temporary pair on one of the other phases. For example, on a two-phase machine an arrangement similar to that shown in Fig. 22 should be made for each of the phases, and when the connections are right, each set of phase lamps will light or

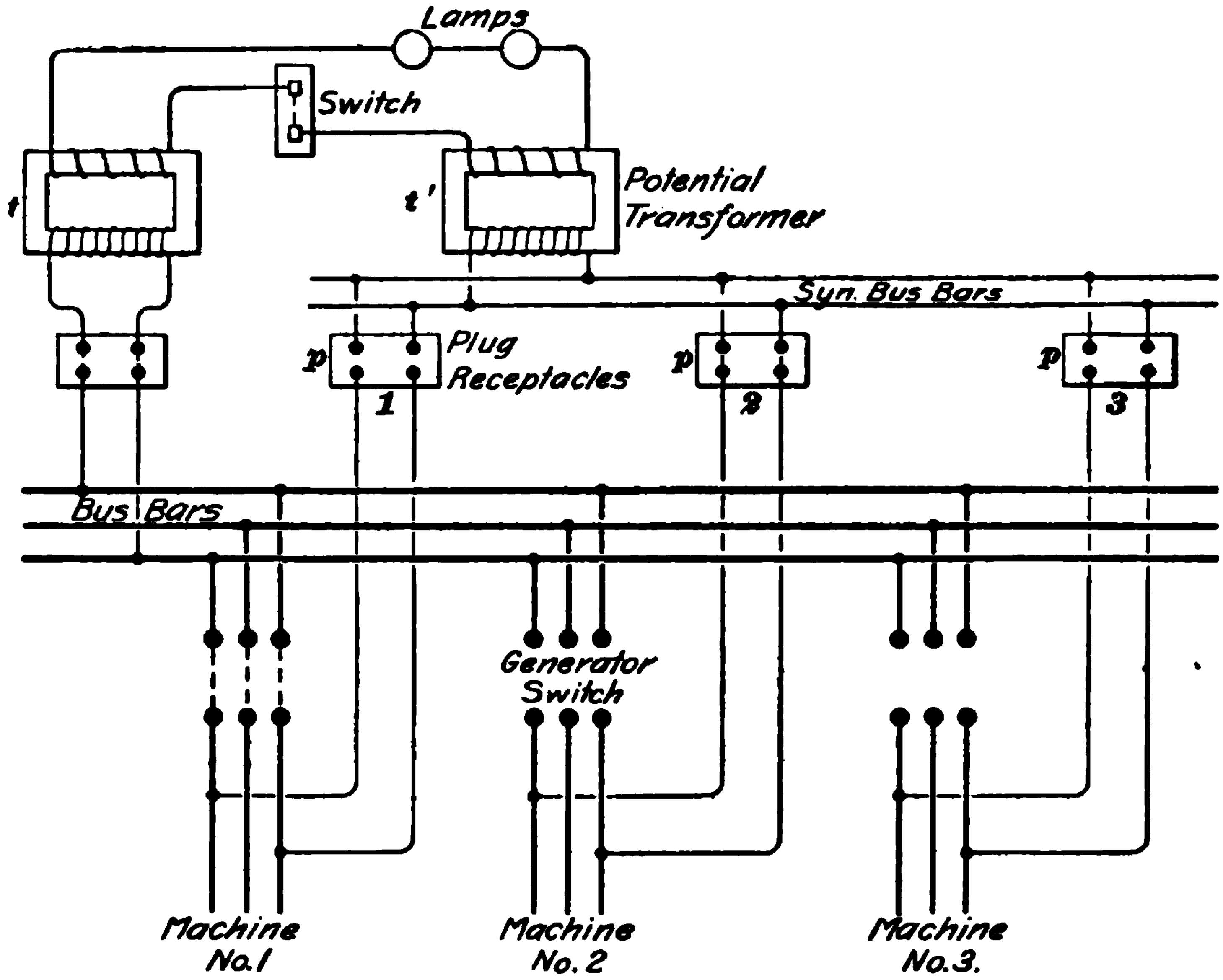


FIG. 23

become dark, as the case may be, at the same instant, showing that both phases are ready for parallel operation. After it is known that the connections are all right, the temporary pair of transformers may be removed and only one pair used, as in Fig. 22.

74. Fig. 23 shows a common scheme of connections used for synchronizing with lamps. In this case the connections are shown for three machines, each machine being provided

with its plug receptacle p. One small transformer t is connected across the bus-bars, and the other t' can be connected to any one of the machines by inserting the plug in its receptacle. For example, suppose the main switch of machine No. 1 is closed, as indicated by the dotted lines, and that it is desired to operate machine No. 2 in parallel with No. 1. Machine No. 2 would be brought up to speed and the plug inserted at receptacle *2*, thus connecting t' to the machine. With the connections as shown, synchronism is indicated when the lamps burn to full brightness, hence the generator switch of machine No. 2 would be thrown in when the lamps are at the middle of a beat and at full brightness. The same arrangement could be used for synchronizing with dark lamps, the only change being that the synchronizing plug would be cross-connected, thus making the transformers oppose each other. Should the alternators generate a low voltage, as is sometimes the case when they are used in connection with step-up transformers or for low-voltage work, it is not necessary to use transformers t, t'. All that is necessary in such cases is to connect the terminals of the synchronizing circuit direct to the machines or bus-bars and insert a sufficient number of lamps in series to stand the maximum voltage applied to them. Another plan in low-voltage work is to use autotransformers that step down the voltage to an amount suitable for the lamps.

75. Use of Voltmeter for Synchronizing.—As explained above, lamps have been used very largely in the past for indicating synchronism, but they are not entirely satisfactory for this purpose. Lamps do not indicate the point of synchronism as closely as desirable, especially when large generating units are involved, and they do not give any accurate idea as to how much the machine being synchronized is out of phase or whether it is coming into or going out of phase. If a large machine is connected to the bus-bars when out of phase, even by a slight amount, a heavy cross-current will flow, and this frequently results in burned switch contacts, to say nothing of possible worse

results. A number of schemes have been adopted for indicating the point of synchronism more exactly than is possible with lamps. Fig. 24 shows an arrangement of connections by which the machine voltmeters are used. If a voltmeter is connected in the same way as synchronizing lamps, the pressure applied to it at synchronism will be either zero or double the ordinary pressure, depending on how the transformers are connected. This would make

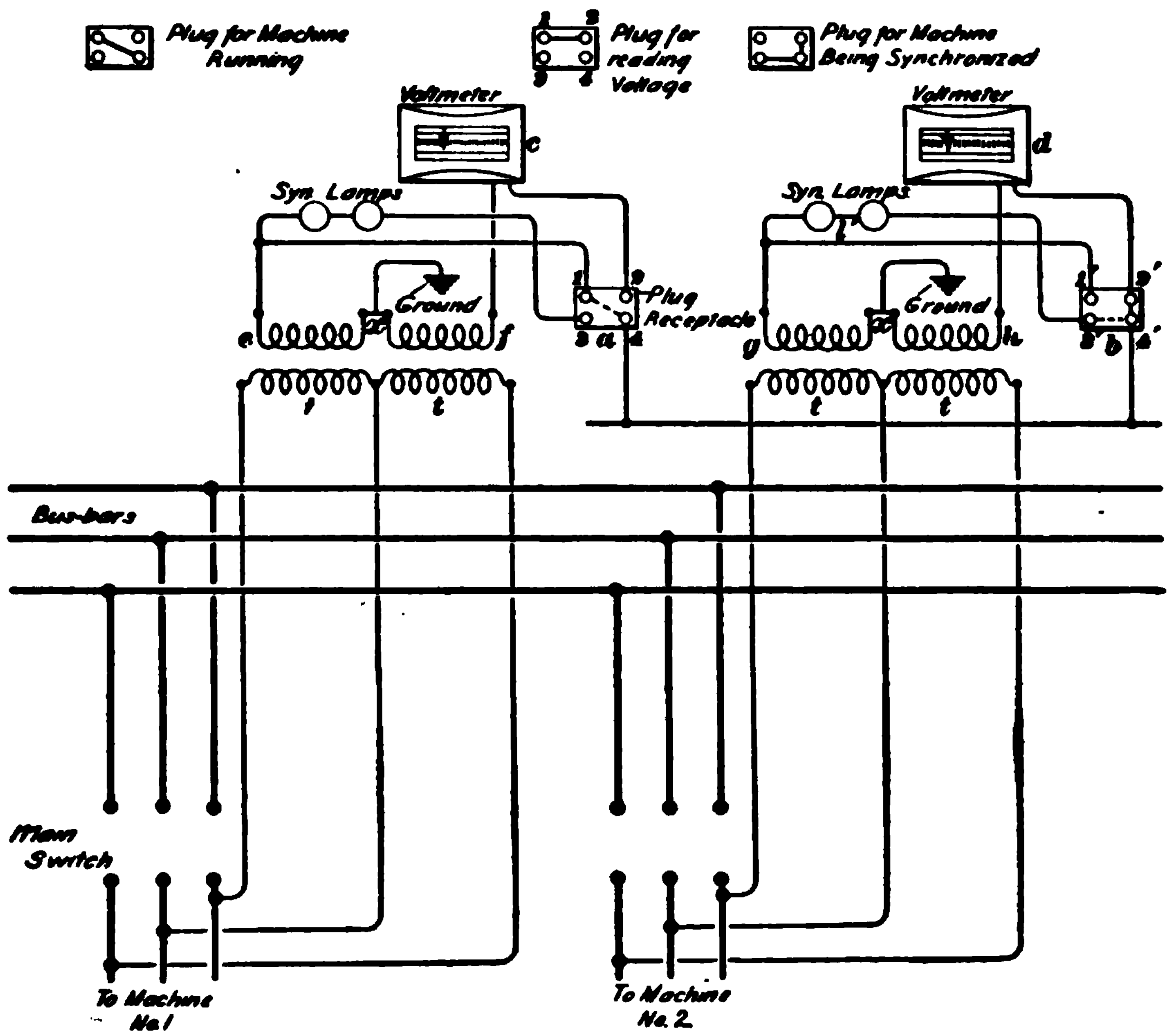


FIG. 24

the point of synchronism, as indicated by the instrument, come either at the zero end of the scale where considerable changes in voltage might make very little change in the reading, or at the maximum point of the swing where a considerable change in phase difference is necessary to cause an appreciable change in the resultant voltage. A scheme for three-phase systems, devised by Mr. J. E. Woodbridge, and shown in Fig. 24, overcomes these objections by

making the voltage applied to the voltmeter at synchronism the resultant of two E. M. F.'s differing in phase by 60° instead of two that are in phase or 180° out of phase, as is ordinarily the case. The two transformer secondaries, connected in series through the voltmeter by means of the synchronizing plug, are attached to two different phases of the three-phase system in such a way that their E. M. F.'s differ in phase by 60°. Thus the resultant E. M. F. applied to the voltmeter is, when the machines are in phase, equal to the normal E. M. F., thus bringing the pointer somewhere near the mid-point of the scale. The rate of change of the resultant E. M. F. due to changes of phase relation is also high with this connection, thus giving a more accurate indication of the exact instant at which the machines are in phase.

In Fig. 24 the connections are shown for a pair of high-pressure alternators, and two potential transformers *t*, *t* are provided for each machine. The junction of the two transformer secondaries is grounded, as shown; this not only simplifies the connections by making the ground serve as one synchronizing bus, but, what is of more importance, it precludes the existence of a high pressure between the switchboard instruments and the ground in case the insulation between primary and secondary should break down. By using suitable plugs in the receptacles *a*, *b*, the voltmeter can be used either to indicate the voltage of the machine, or for synchronizing purposes; lamps are also provided, as shown, to indicate synchronism along with the voltmeter. The plug for the machine that is already in operation connects points *1* and *4*, as shown at *a*, and the plug for the machine being synchronized connects points *2'*, *4'*, *3'*, as shown at *b*. This connects voltmeter *d* in series (by way of the ground connections) with coils *e* and *h*, and the lamps in series with coils *e* and *g*. The E. M. F.'s of *e* and *h* differ in phase by 120°, but the coils are connected in opposition so that one E. M. F. is reversed with respect to the other and the two E. M. F.'s which combine to act on the voltmeter differ in phase by 60°, as previously mentioned.

The E. M. F.'s of *e* and *g* are in phase so that the voltmeter will indicate normal voltage, and the lamps *l'* will be dark at synchronism. When the voltmeter is to be used in the regular way to indicate the machine voltage, a plug is inserted that connects the upper contacts *1'*, *2'*, thus connecting the voltmeter across the transformer and indicating the voltage between the outside wires.

76. Lincoln Synchronizer.—Voltmeters and other devices are used in many ways to indicate synchronism, and it is impossible to here treat all the different methods. Also, a number of synchronism indicators, or synchronoscopes, have been brought out; Fig. 25 shows one of these devised by Mr. Paul M. Lincoln. The terminals of the potential transformers are connected to the binding posts *a a*, *b b*, and when the incoming machine is in synchronism, the hand *h* remains stationary in the vertical position. If the machine that is being brought into synchronism is running too fast, the hand revolves slowly to the right; if running too slow, it moves to the left. The following description of the principle of operation of this instrument is that given by Mr. Lincoln.

FIG. 25

Suppose a stationary coil *F* has suspended within it a coil *A*, free to move about an axis in the planes of both coils and including a diameter of each. If an alternating current be passed through both coils, *A* will take up a position with its plane parallel to *F*. If, now, the currents in *A* and *F* be reversed with respect to each other, coil *A* will take up a position 180° from its former position. Reversal of the relative directions of currents in *A* and *F* is equivalent to changing their phase relation by 180°, and therefore this change of

180° in phase relation is followed by a corresponding change of 180° in their mechanical relation. Suppose, now, that instead of reversing the relative direction of currents in *A* and *F*, the change in phase relation between them be made gradually and without disturbing the current strength in either coil. It is evident that when the phase difference between *A* and *F* reaches 90°, the force between *A* and *F* will become zero, and a movable system, of which *A* may be made a part, is in condition to take up any position demanded by any other force. Let a second member of this movable system consist of coil *B*, which may be fastened rigidly to coil *A*, with its plane 90° from that of coil *A*, and with the axis of *A* passing through a diameter of *B*. Further, suppose a current to circulate through *B*, whose difference in phase relative to that in *A* is always 90°. It is evident under these conditions that when the difference in phase between *A* and *F* is 90°, the movable system will take up a position such that *B* is parallel to *F*, because the force between *A* and *F* is zero, and the force between *B* and *F* is a maximum; similarly, when the difference in phase between *B* and *F* is 90°, *A* will be parallel to *F*; that is, beginning with a phase difference between *A* and *F* of 0°, a phase change of 90° will be followed by a mechanical change in the movable system of 90°, and each successive change of 90° in phase will be followed by a corresponding mechanical change of 90°. For intermediate phase relations, it can be proved that under certain conditions the position of equilibrium assumed by the movable element will exactly represent the phase relations; that is, with proper design, the mechanical angle between the plane of *F* and that of *A*, and also between the plane of *F* and that of *B*, is always equal to the phase angle between the current flowing in *F* and the currents in *A* and *B*, respectively.

77. Fig. 26 shows the general arrangement of the instrument. As seen from the figure, the construction is similar to that of a small motor. The field *A A* is built up of iron laminations, and is wound with coils *F*, *F* that are connected

in series and joined to the secondary of the potential transformer whose primary is connected to the bus-bars. The armature core B is of the drum type, and is wound with two coils C and D that are approximately at right angles to each other. These coils are connected in series, and their junction x is connected to the middle ring *2* of three collector rings mounted on the shaft. The other two terminals are connected to rings *1* and *3*. The middle ring, through its brush, connects directly to one terminal of the potential transformer of the machine to be synchronized. Ring *3* connects to a choke coil or inductance L; ring *1* connects to one terminal of a non-inductive resistance R. The remaining terminals of R and L are joined to y and connect to the other terminal of the potential transformer. The inductance L and resistance R are adjusted so that the currents in the coils C and D differ in phase by very nearly 90°. The current in the coils F, F will lag nearly 90° behind the E.M.F. E, because of the high inductance of the field coils; consequently, the magnetism set up by the field will be 90° behind the E.M.F. E. When the current in coil D is in

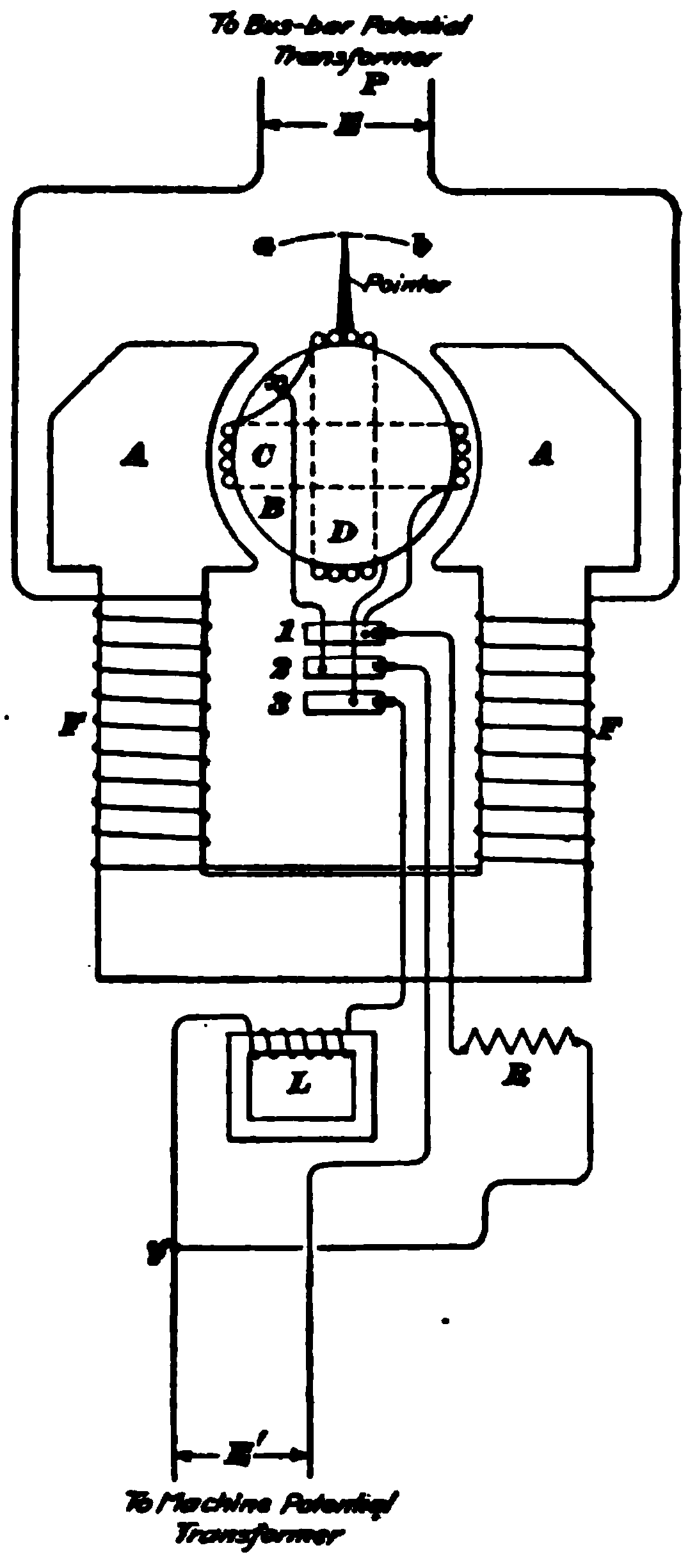


FIG. 26

phase with the field magnetism, D will swing around until it assumes the vertical position where its plane is at right angles to that of the field. The current in D is 90° behind E', because of the inductance L; hence, at synchronism the current in D is in phase with the field magnetism, and the pointer assumes the vertical position. The current

in C is in phase with E', and hence differs in phase from the field current by 90°; hence, at synchronism no torque is exerted on coil C if the frequencies of E and E' are equal. But if E and E' differ in phase by 90°, then the current in D is at right angles to the field and the current in C is in phase with the field magnetism; consequently, coil C assumes the vertical position, and the hand swings around through 90°. For a phase difference of less than 90° the pointer assumes an intermediate position. If the machines do not have equal frequencies, i. e., if the machine being synchronized is running too fast or too slow, the phase difference between the field on one hand and C and D on the other is constantly changing, and, therefore, the pointer will revolve at a speed depending on the difference in speed of the alternators. From the direction of rotation, the attendant can tell at once whether the machine being synchronized requires speeding up or slowing down. The synchronizers made by the General Electric and Westinghouse companies operate on the above principle, and are now generally used instead of lamps or voltmeters.

78. The foregoing will give a general idea as to some of the methods in common use for indicating synchronism. As before stated, there are a great many possible arrangements and modifications of the connections, but the principles involved are much the same in all of them. Some devices have been proposed to make the action of synchronizing automatic; that is, to close the main switch automatically when the point of synchronism is reached instead of leaving the time of closing to the judgment of the operator. The object is to prevent the machines from being thrown together at the wrong time, and although a number of such automatic devices have been patented, they have not as yet come into general use. One arrangement for closing the switch is that patented by Mr. Lincoln in connection with the synchronizer just described. An electrical contact is arranged so that a circuit will be established when the pointer is anywhere within an arc, such as a b,

Fig. 26. This arc represents the amount of phase difference that is allowable and yet have the machines go together without making a disturbance. The current through this electric contact operates a switch or relay that in turn closes the main switch. It is necessary that the relay shall only operate when the pointer is revolving at a very low speed; or, in other words, when contact exists for a considerable time. This is accomplished by providing the relay with a dashpot that prevents it from closing unless the current through its magnet is maintained for an appreciable length of time. If this were not done, the machines would be thrown together when their frequencies were unequal, because the hand in its revolution would make contact with the arc and close the circuit. It is only when the hand is moving very slowly that the switch should be operated.

FEATURES CONNECTED WITH PARALLEL OPERATION

79. When two alternators are running in parallel, each will hold the other in step and they will each run at such a speed as to give the same frequency; if the alternators have the same number of poles, their speeds will be exactly the same. When direct-current generators are operated in parallel, they do not necessarily run at the same speed and the load carried by each machine can be varied by changing the field excitation. When the load is increased, the engine speed drops a little and the governor admits more steam to the cylinders, thus increasing the power supplied. In the case of alternators, the machines are compelled to run at the same speed, and each alternator will deliver power in proportion to the power supplied to it from its prime mover. Changing the field excitation will not change the power delivered; the only effect of changing the field strength will be to set up local currents between the machines. The field strength should be adjusted so that, for a given total current delivered, the current delivered by each machine will be a minimum; or, so that the sum of the currents as indicated by the machine ammeters will equal the total current as nearly as possible.

The problem, then, of making a proper division of the load is more difficult in the case of alternators than direct-current machines. The alternators are compelled to run at the same speed just as if they were actually geared to a common shaft, and any decrease in the speed of one must be accompanied by a corresponding decrease of speed in the other. Now, the governors of steam engines and water-wheels are designed so that a certain small decrease in speed is necessary, with increase of load, to make them operate. For example, suppose a steam engine is carrying a light load and running at a certain speed. If the load is increased, the speed must drop a slight amount before the governor can operate to admit steam sufficient to carry the load, and the engine continues to run at a slightly lower speed on the heavy load than it did on the light load. There is therefore a certain engine speed for each load.

Now, suppose that two alternators are running in parallel and that each is supplying half the amount of power taken by the system. If the external load is increased, the amount of power supplied to each alternator must also increase, and, if the load on the machines is to be kept equal, each engine must increase its power output by an equal amount. We have just seen that to increase the power output the engine speed must drop slightly, and as the alternators must always run in synchronism, it follows that both engines must, for a given increase in load, drop their speeds an equal amount. In other words, to secure equal division of load the engines must perform in exactly the same way as regards change in speed with change in load. If one drops its speed more than the other, it takes the load and the other machine may even be driven as a synchronous motor. The question, then, of proper division of load is one that relates more to the engines than to the alternators, and in choosing engines for this kind of work every effort should be made to have them alike as regards their change in speed with change in load. The engines may run at exactly the same speed for a given load, but if their speeds do not drop by the same amount with increase in load, the output will not divide properly between the machines.

When machines are belt-driven, great care must be taken to see that the pulleys are exactly the correct dimensions to give the speeds required for operating in synchronism; because, if this is not the case, there will be considerable belt slippage, and there will also be considerable cross-current between the two machines.

80. Hunting of Alternators.—When alternators are coupled directly to slow-moving steam engines, difficulty is frequently encountered in connection with their parallel operation. This is specially the case when the alternators deliver a current of high frequency. The machines **surge,** or **hunt,** that is, the speed may fluctuate during each revolution, thus causing large periodic cross-currents to flow between the machines and seriously affecting the voltage of the system. This surging may become so bad as to cause the machines to fall out of synchronism and render parallel operation impossible. If rotary converters or synchronous motors are operated from the alternators, surgings are also set up in them and the voltage fluctuation and sparking caused thereby may be so serious as to make satisfactory operation very difficult to accomplish.

The cause of these surgings has been found in many cases to be due to periodic variations in the speed of the engine, and various methods have been tried to suppress them. The turning effort exerted on the crankpin of a steam engine is not uniform at all parts of the stroke, the pressure at the various points depending on the steam distribution in the cylinder or cylinders, on the position of the crankpin, angularity of the connecting-rod, etc. The result is, that while the speed of the engine may remain practically constant so far as the number of revolutions per minute is concerned, there will be momentary variations in speed during each revolution. It takes but a small momentary variation in angular velocity to throw the machines considerably out of phase, especially if the alternator has a large number of poles. For example, if a direct-connected alternator has 60 poles, the angular distance between centers of

poles will be 6°, and this corresponds to a phase difference of 180°. The periodic variation in the angular velocity of the revolving field or armature sets up corresponding variations in phase difference and results in periodic surges of current between the machines. This trouble has been investigated quite fully by Mr. W. L. R. Emmett*, who found that the energy necessary to maintain these current oscillations was in a number of cases supplied from the steam cylinders of the engines, and that it could be largely prevented by fixing the governor so that it would not respond to these sudden variations and admit the steam necessary to maintain them. The governor must, however, be capable of responding to changes in the regular load on the machine, otherwise enough power would not be furnished to the alternator to enable it to carry its share of the load. In order to fix the governor so that it would respond to gradual changes in the load, but not to momentary oscillations, it was provided with a dashpot similar to that shown in Fig. 27. This dashpot was designed by Messrs. H. W. Buck and Harte Cook. It consists of a cylinder *A* in which a piston *B* moves; two by-passes *b*, *b'* are provided, and at the end of each is placed a valve *c* or *c'* ordinarily held closed by springs *d*, *d'*. Each valve is provided with a small by-pass *e*, *e'*, and the whole cylinder, including the ports, is filled with

Fig. 27

*Transactions of American Institute of Electrical Engineers, October 25, 1901.

heavy oil. Unless valves *c*, *c'* are raised, the only passage for the oil, to allow movement of the piston, is through the small ports, and the piston is therefore practically locked. A sudden fluctuation in the governor will not move *c* or *c'*, but a steady pressure on the piston, due to a prolonged raising or lowering of the speed, will move them, and the oscillations of the governor and steam in the cylinders are thereby damped out, thus suppressing the hunting action of the alternators.

81. In order to prevent hunting effects, engine builders have endeavored to secure uniform angular velocity of their engines. In some cases this is accomplished by the use of very heavy flywheels, but it is a question whether heavy flywheels are on the whole advisable. Some authorities claim that the momentum of heavy flywheels tends to maintain the oscillations, and that it is better to use fairly light flywheels and design the engine so that the turning effort on the shaft will be nearly uniform. By using two or more engines coupled to the same shaft with their cranks at the proper angle to each other, this result can be attained quite closely. This is readily accomplished by cross-compound engines, either horizontal or vertical, and both types are largely used for driving alternators. In the case of the large alternators of the Manhattan Elevated Railway, New York, each alternator is driven by four engines, two of which are vertical and two horizontal. There is a crankpin at each end of the shaft, and to it is connected one vertical and one horizontal engine. The cranks are displaced 135° and since the four cylinders give eight impulses during each revolution, the turning moment is so uniform that no flywheel other than the revolving field of the alternator is necessary.

82. Use of Damping Devices.—Another method that has been used to prevent hunting is to provide special windings or conductors on the alternator field, so that the currents set up in them will oppose any shifting action and thus retard the oscillations. This device has been used much more on European alternators than on those built in America.

Fig. 28 (*a*) shows the method of arranging a damper (French amortisseur) of this kind, due to Hutin and Leblanc. *A* is the laminated pole piece of a revolving field alternator and is provided with the usual exciting coil *B*. Near the surface of the pole piece are a number of slots in which copper bars *c* are placed. These bars are connected together at each end of the pole by means of copper straps, thus forming the bars into a number of closed circuits similar to the squirrel-cage armature of an induction motor. As long as the magnetic flux passing from the pole face into the armature remains stationary with respect to the pole face, no currents are set up in the bars. If, however, there is any momentary shifting of the field, heavy currents are set up in the bars, and

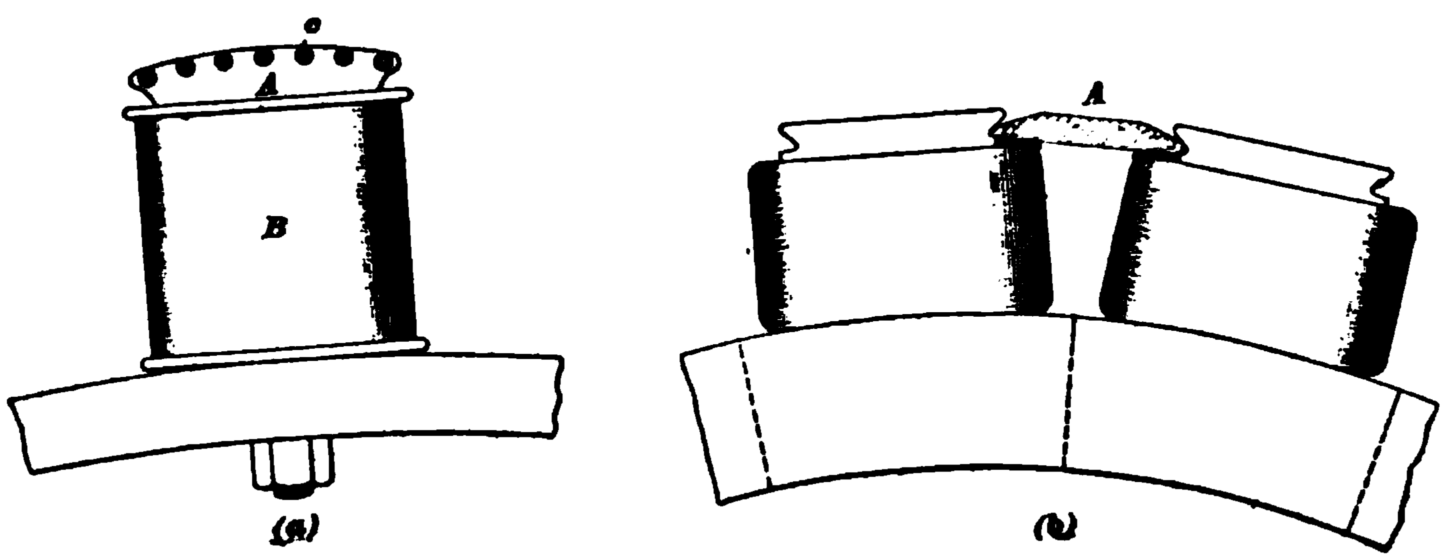


Fig. 28

these currents dampen the motion, thus smoothing out any tendency toward fluctuation. Fig. 28 (*b*) shows a field construction used by the Westinghouse Company that has somewhat the same effect. Copper bridges *A* are placed between the poles; these serve to hold the coils in place and dampen hunting effects.

83. Hunting sometimes occurs even when the alternators are driven by prime movers, such as steam or water turbines, that give an absolutely uniform angular velocity. In this case the effect is due to certain relations between the properties of the electric circuit, such as its self-induction, capacity, etc., and the momentum of the moving masses of the machinery. The result is a cumulative pendulum effect that may be overcome by changing some of the above properties

of the circuit or by damping the alternator, synchronous motors, rotary converters, or other devices on the system. For example, a change in field excitation will frequently overcome the difficulty. Fig. 29 shows another arrangement used for preventing hunting of rotary converters and alternators. The pole piece is provided with a slot *b* in the center, in which is placed a heavy copper bar. The pole is also encircled by a heavy conductor forming two local circuits, in which heavy currents are set up if there is any shifting of the field. Rotary converters are also frequently provided with copper bridges between the poles, about as shown in Fig. 28 (*b*), to dampen the hunting. Fig. 30 shows an anti-hunting device used on General Electric converters. The copper casting *a*, *b*, *e*, *f* bridges across the pole tips and is held in place by a bolt passing through *a b*. By drawing up this bolt, edges *e f* are forced apart against the pole tips. The sides *c d* lie in slots provided in the pole faces.

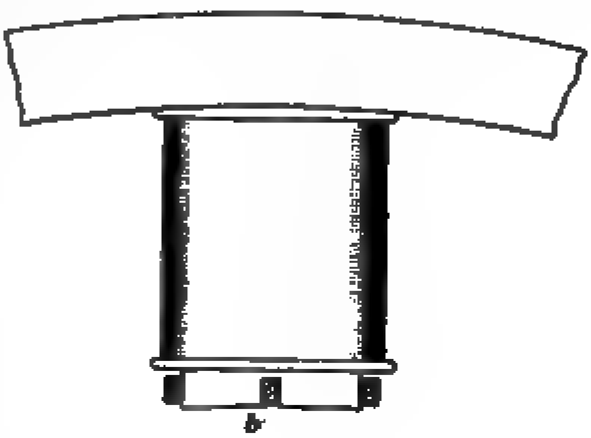


FIG. 29

84. Generally speaking, the practice in America is to obtain engines that will give a nearly uniform angular velocity, though damping devices are also used. Damping devices add to the cost and also slightly lower the efficiency of the machines to which they are applied. Engine builders will now guarantee engines not to give a departure from uniform motion during a revolution that will cause more than $2\frac{1}{2}°$ to $3°$ of phase displacement of the E. M. F. furnished by each of the alternators or a total maximum phase displacement of $5°$ to $6°$. If the displacement does not exceed this amount, the operation should be satisfactory. In America

damping devices are more commonly used on rotary converters than on alternators.

When steam-driven alternators are being synchronized, it is necessary to have some convenient means of controlling the engine speed from the switchboard. One way of doing this is to have a small reversible electric motor attached to the governor and arranged so that it can vary the tension on a spring attached to the governor weights or vary the position of a weight on a lever arm attached to the governor. This motor is readily started, stopped, or reversed from the switchboard, so that the attendant has the speed of the engine under control and can make the slight variations in speed necessary to secure equality of frequency. Also, this device allows the point of cut-off to be varied when the engine is in regular operation, thus regulating the amount of power supplied to the alternator. As explained above, the current delivered by each alternator when running in synchronism depends on the amount of power supplied to the alternator, so that by adjusting the governor, the output of each machine, as shown by its indicating wattmeter on the switchboard, can be regulated.

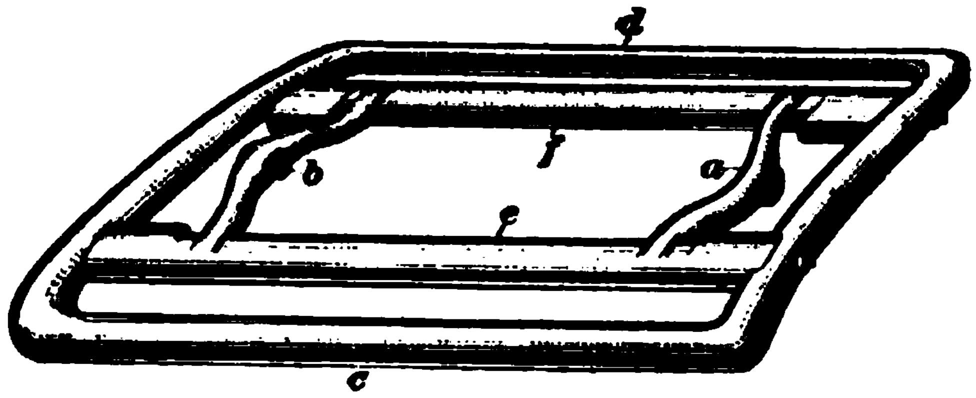


FIG. 30

85. Compound-Wound Alternators in Parallel. Most of the large alternators now installed are of the revolving field type and are not generally provided with a compound field winding. For large units it is found that a carefully designed machine gives sufficiently close voltage regulation with a plain, separately excited winding, so that the extra complication of compound field excitation is not warranted. Where a compound winding is used on the fields, it is necessary to provide an equalizing connection somewhat similar to that used for a direct-current machine. Fig. 31 shows the connections necessary for running two

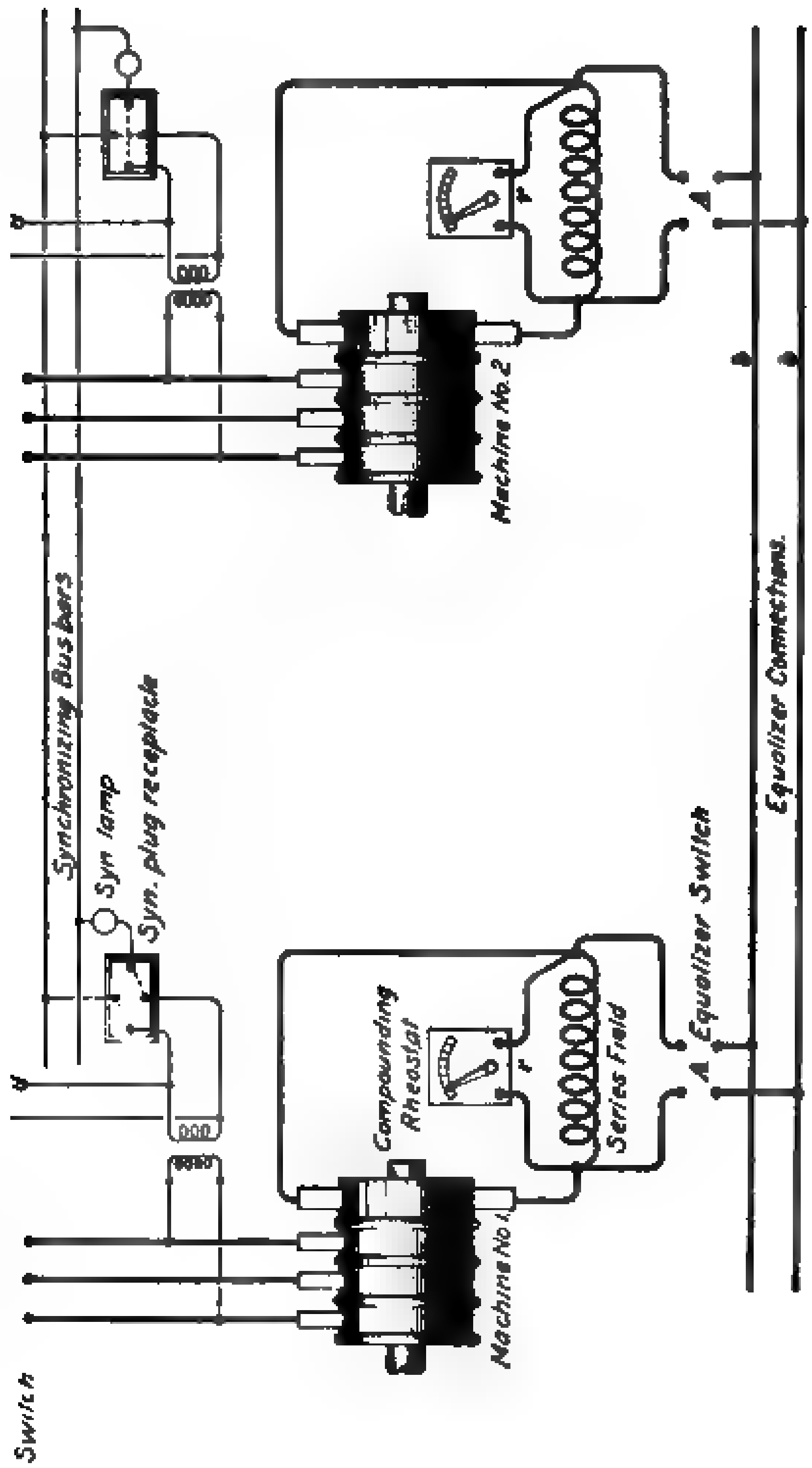

Synchronizing Bus bars
Syn lamp
Syn. plug receptacle
a
a
Machine No. 2
Machine No. 1
Compounding Rheostat
r
r
Series Field
A
A
Equalizer Switch
Equalizer Connections.
Switch

FIG. 31

compound-wound, three-phase alternators in parallel, the connections for the separately excited field being omitted in order to simplify the diagram. The terminals of the series-field winding on each machine connect through switches *A*, *A* to the equalizing wires *b*, *b*. An adjustable resistance *r* is connected across each field, so that the effect of the series-coils can be varied to suit the character of the load on the machines. With the synchronizing connections shown in the figure, the lamps will be bright at synchronism, though the lamps could be made dark by simply changing the cross-connections used with the plug on the machine being synchronized. In this case an ammeter is used in one phase only, and is all that is necessary to indicate the current, provided the load is of such a nature that it is not liable to become unbalanced. In many cases it is customary to use an ammeter in each line, so that the current in all three phases will be indicated.

LINE CONSTRUCTION

INTRODUCTION

1. Line construction may be considered conveniently under two heads: (*a*) *overhead construction;* (*b*) *underground construction.*

For nearly all work in towns and small cities or for cross-country work, the lines are supported on poles. In cities, the current is now usually distributed, at least so far as the central part of the cities is concerned, by means of wires or cables run in underground tubes or ducts. This method is, of course, much more expensive than the overhead method; but the large increase in the number of wires used for different electrical purposes has rendered underground distribution in cities almost absolutely necessary.

LINE CONDUCTORS

2. The line wire is, in the vast majority of cases, of *copper*. *Aluminum* is now coming into use for this purpose, and in the future it may replace copper for some lines of work. *Iron* or *steel* is seldom used for a line conductor, because its resistance is too high. There is one case, however, in which it is largely used as a return conductor, and that is in connection with electric railways, where the current is led back to the power house through the rails.

COPPER CONDUCTORS

3. Bare and Insulated Wires.—Line conductors are usually in the form of **copper wire** of round cross-section whenever the conductor is of moderate size. For conductors

of large cross-section, stranded cables are used, made up of a number of strands of small wire twisted together. This construction makes the conductor flexible and easy to handle. When these wires or cables are strung in the air, they are usually insulated by a covering that consists of two or three

FIG. 1

braids of cotton, soaked in a weather-proof compound composed largely of pitch or asphalt. For underground work, the conductor is first insulated with rubber, or paper soaked in

FIG. 2

compound, and the whole covered with a lead sheath to keep out moisture. Fig. 1 shows a stranded cable for underground work provided with an insulating layer of paper and a lead

FIG. 3

sheath. Fig. 2 shows an ordinary triple-braid weather-proof overhead line wire, and Fig. 3 a weather-proof overhead cable. When the pressure used on the line is very high, say 10,000 volts or more, bare wires are generally used, because the ordinary weather-proof insulation is of little or no

protection against such pressures and only gives a false appearance of security. The practice for such lines is, therefore, to use bare wire and to insulate it thoroughly by means of specially designed insulators.

WIRE GAUGES

4. Various standards or **wire gauges** have been adopted by different manufacturers, but the safest and best way is to express the diameter of a wire in *mils*, or thousandths of an inch, and its area of cross-section in *circular mils.* The American, or Brown & Sharpe, gauge is used almost exclusively in America in connection with electrical work, but it is always well to give the diameter of the wire as well as its gauge number, so as to avoid any possibility of mistake. When wires or cables larger than the regular B. & S. sizes are specified, their cross-section is given in circular mils. Explanations regarding the B. & S. gauge and the expression of area in circular mils, etc. have already been given, so it will not be necessary to repeat them here. As we shall have occasion to refer to the B. & S. wire table frequently, Table I is repeated here for convenience. This gives the dimensions, weight, etc. of bare copper wire according to the B. & S. gauge for both annealed and hard-drawn wire; most wires and cables are of annealed copper. The use of hard-drawn copper is confined principally to trolley wire for street railways and telephone and telegraph line wires.

5. Table II gives the approximate weights of weather-proof line wire, such as is used for ordinary outside lines.

6. Table III gives the approximate dimensions of strandard insulated weather-proof cables for overhead work. Such cables are always designated by their area of cross-section in circular mils, and not by gauge number. In fact, any conductor larger than No. 0000 is usually designated by its area in circular mils. Cables such as those given in Table III are extensively used for street-railway feeders or for any other purpose requiring a large conductor.

TABLE I

DIMENSIONS, WEIGHT, ETC. OF BARE COPPER WIRE

American, or B. & S., Gauge

Gauge No., B. & S.	Diameter in Mils, or $\frac{1}{1000}$ Inch	Area in Circular Mils			…unds per …ile	Feet per Pound	Ohms per Pound, Annealed	Resistance at 68° F., in International Ohms, Based on Matthiessen's Standard				
					…—Specific Gravity, 8.89			Ohms per 1,000 Feet		Ohms per Mile		Feet per Ohm, Annealed
	d	d^2						Pure Annealed	Hard Drawn	Pure Annealed	Hard Drawn	
0000	460.000	211,6			81.4	1.561	.00007639	.04893	.050036	.25835	.26419	20,440.
000	409.640	167,8			82.2	1.969	.0001215	.06170	.063094	.32577	.33314	16,210.
00	364 800	133,079.4	.10452	402.8	2,126.8	2.482	.0001931	.07780	.079558	.41079	.42007	12,850.
0	324 865	105.534.5	.082887	319.5	1,686.9	3.130	.0003071	.09811	.10033	.51802	.52973	10,190.
1	289.300	83,694.2	.065732	253.3	1,337.2	3.947	.0004883	.1237	.12649	.65314	.66790	8,083.
2	257.630	66,373.0	.052128	200.9	1,060.6	4.977	.0007765	.1560	.15953	.82368	.84239	6,410.
3	229.420	52,634.0	.041339	159.3	841.09	6.276	.001235	.1967	.20114	1.0386	1.0621	5,084.
4	204 310	41,742.0	.032784	126.4	667.39	7.914	.001963	.2480	.25361	1.3094	1.3392	4,031.
5	181.940	33,102.0	.025999	100.2	529.06	9.980	.003122	.3128	.31987	1.6516	1.6889	3,197.
6	162.020	26,250.5	.020618	79.46	419.55	12.58	.004963	.3944	.40332	2.0825	2.1295	2,535.
7	144.280	20,816.0	.016351	63.02	332.75	15.87	.007892	.4973	.50854	2.6258	2.6850	2,011.
8	128.490	16,509.0	.012967	49.98	263.89	20.01	.01255	.6271	.64127	3.3111	3.3859	1,595.
9	114.430	13,094.0	.010283	39.63	209.24	25.23	.01995	.7908	.80876	4.1753	4 2769	1,265.
10	101.890	10,381.0	.0081548	31.43	165.95	31.82	.03173	.9972	1.0199	5.2657	5.3848	1,003.
11	90.742	8,234.0	0064656	24.93	131.63	40.12	.05045	1.257	1.2854	6.6369	6.7869	795.3
12	80.808	6,529.9	.0051287	19.77	104.39	50.59	.08022	1.586	1.6218	8 3741	8.5633	630.7

13	71.961	5,178.4	.0040672	15.68	82.791	63.79	.1276	1.999	2.0443	10.555	10.794	500.1
14	64.084	4,106.8	.0032254	12.43	76.191	80.44	.2028	2.521	2.5779	13.311	13.612	396.6
15	57.068	3,256.7	.0025579	9.858	52.050	101.4	.3225	3.179	3.2508	16.785	17.165	314.5
16	50.820	2,582.9	.0020285	7.818	41.277	127.9	.5128	4.009	4.0996	21.168	21.646	249.4
17	45.257	2,048.2	.0016087	6.200	32.736	161.3	.8153	5.055	5.1692	26.691	27.294	197.8
18	40.303	1,624.3	.0012757	4.917	25.960	203.4	1.296	6.374	6.5183	33.655	34.416	156.9
19	35.890	1,288.1	.0010117	3.899	20.595	256.5	2.061	8.038	8.2196	42.441	43.400	124.4
20	31.961	1,021.5	.00080231	3.092	16.324	323.4	3.278	10.14	10.372	53.539	54.749	98.66
21	28.462	810.1	.00063626	2.452	12.946	407.8	5.212	12.78		67.479		78.24
22	25.347	642.4	.00050457	1.945	10.268	514.2	8.287	16.12		85.114		62.05
23	22.571	509.45	.00040015	1.542	8.142	648.4	13.18	20.32		107.29		49.21
24	20.100	404.01	.00031733	1.223	6.457	817.6	20.95	25.63		135.53		39.02
25	17.900	320.40	.00025166	.9699	5.121	1,031.	33.32	32.31		170.59		30.95
26	15.940	254.10	.00019958	.7692	4.061	1,300.	52.97	40.75		215.16		24.54
27	14.195	201.50	.00015827	.6100	3.221	1,639.	84.23	51.38		271.29		19.46
28	12.641	159.79	.00012551	.4837	2.554	2,067.	133.9	64.79		242.09		15.43
29	11.257	126.72	.000099536	.3836	2.025	2,607.	213.0	81.70		431.37		12.24
30	10.025	100.50	.000078936	.3042	1.606	3,287.	338.6	103.0		543.84		9.707
31	8.928	79.70	.000062599	.2413	1.274	4,145.	538.4	129.9		685.87		7.698
32	7.950	63.21	.000049643	.1913	1.010	5,227.	856.2	163.8		864.87		6.105
33	7.080	50.13	.000039368	.1517	.801	6,591.	1,361.	206.6		1,090.8		4.841
34	6.305	39.75	.000031221	.1203	.635	8,311.	2,165.	260.5		1,375.5		3.839
35	5.615	31.52	.000024759	.09543	.504	10,480.	3,441.	328.4		1,734.0		3.045
36	5.000	25.00	.000019635	.07568	.400	13,210.	5,473.	414.2		2,187.0		2.414
37	4.453	19.83	.000015574	.06001	.317	16,660.	8,702.	522.2		2,757.3		1.915
38	3.965	15.72	.000012345	.04759	.251	21,010.	13,870.	658.5		3,476.8		1.519
39	3.531	12.47	.0000097923	.03774	.199	26,500.	22,000.	830.4		4,384.5		1.204
40	3.145	9.89	.0000077634	.02993	.158	33,410.	34,980.	1,047.		5,528.2		.955

ALUMINUM CONDUCTORS

7. Mention has already been made of the fact that **aluminum** is being used for electrical conductors, because this metal can now be sold at a figure low enough to compete with copper. Its conductivity is only about 60 per cent. that of copper, so that for a conductor of the same resistance a larger cross-section is required. Aluminum is, however, so much lighter than copper that the larger cross-section can be used and still compete with the latter metal, although the cost per pound of the aluminum is considerably

TABLE II

APPROXIMATE WEIGHTS OF WEATHER-PROOF WIRE

(*American Electrical Works*)

TRIPLE-BRAIDED INSULATION

Size	Feet per Pound	Pounds per 1,000 Feet	Pounds per Mile	Carrying Capacity, Amperes, National Board Fire Underwriters
0000	1.34	742	3,920	312
000	1.64	609	3,215	262
00	2.05	487	2,570	220
0	2.59	386	2,040	185
1	3.25	308	1,625	156
2	4.10	244	1,289	131
3	5.15	194	1,025	110
4	6.26	160	845	92
5	7.46	134	710	77
6	9.00	111	585	65
8	13.00	73	385	46
10	20.00	50	265	32
12	29.00	35	182	23
14	38.00	26	137	16
16	48.00	21	113	8
18	67.00	15	81	5

TABLE II—(*Continued*)

DOUBLE-BRAIDED INSULATION

Size	Feet per Pound	Pounds per 1,000 Feet	Pounds per Mile	Carrying Capacity, Amperes, National Board Fire Underwriters
0000	1.40	711	3,754	312
000	1.75	570	3,010	262
00	2.29	436	2,300	220
0	2.81	355	1,875	185
1	3.56	281	1,482	156
2	4.49	223	1,175	131
3	5.45	184	969	110
4	6.82	147	774	92
5	9.10	110	580	77
6	10.35	97	510	65
8	15.52	64	340	46
10	22.00	45	237	32
12	40.00	25	132	23
14	56.00	18	95	16
16	76.00	13	69	8
18	100.00	10	53	5

higher. Line-construction work is somewhat more difficult with aluminum than with copper; joints are more difficult to make and there is greater liability of the spans breaking. Table IV gives the properties of aluminum wire of the grades made by the Pittsburg Reduction Company and Table V gives the resistance. The values in these tables are taken from a pamphlet issued by the above company. A comparison of some of the properties of aluminum and copper is given in Table VI.

TABLE III

STANDARD WEATHER-PROOF FEED-WIRE

(Roebling's)

Circular Mils	Outside Diameters Inches	Weights Pounds 1,000 Feet	Weights Pounds Mile	Approximate Length on Reels Feet	Carrying Capacity, National Board Fire Underwriters
1,000,000	$1\frac{1}{2}$	3,550	18,744	800	1,000
900,000	$1\frac{13}{32}$	3,215	16,975	800	920
800,000	$1\frac{11}{32}$	2,880	15,206	850	840
750,000	$1\frac{5}{16}$	2,713	14,325	850	
700,000	$1\frac{9}{32}$	2,545	13,438	900	760
650,000	$1\frac{1}{4}$	2,378	12,556	900	
600,000	$1\frac{7}{32}$	2,210	11,668	1,000	680
550,000	$1\frac{3}{16}$	2,043	10,787	1,200	
500,000	$1\frac{1}{8}$	1,875	9,900	1,320	590
450,000	$1\frac{3}{32}$	1,703	8,992	1,400	
400,000	$1\frac{1}{16}$	1,530	8,078	1,450	500
350,000	1	1,358	7,170	1,500	
300,000	$\frac{15}{16}$	1,185	6,257	1,600	400
250,000	$\frac{29}{32}$	1,012	5,343	1,600	

TABLE IV

RESISTANCE, TENSILE STRENGTH, AND WEIGHT OF ALUMINUM LINE WIRE

Grade	Conductivity Pure Copper = 100	Comparative Section of Equal Conductivity Copper = 100	Comparative Weight of Same Lengths of Equal Conductivity Copper = 100
A 0	62	156.4	47.
A 75	58	167.0	50.2
A 2	54	180.0	54.

No. in B. & S. Gauge	Diameter in Mils d	Circular Mils d^2	Area in Square Inches $\frac{d^2 \times .7854}{1,000,000}$	Grade A 0		Grade A 75		Grade A 2		Pounds per Mile. Sp. Gr. 2.68 Water, 62.355 lb. per Cu. Ft.	Pounds per Mile of Aluminum Having Same Resistance as Copper Wire of Size Given. Grade A 75
				Resistance per 1,000 Feet at 75° F.	Tensile Strength, Pounds per Square Inch	Resistance per 1,000 Feet at 75° F.	Tensile Strength, Pounds per Square Inch	Resistance per 1,000 Feet at 75° F.	Tensile Strength, Pounds per Square Inch		
4	204.31	41,742.0	.0327840	.4012	27,000	.4288	33,000	.4605	40,000	200.90	336.0
5	181.94	33,102.0	.0259980	.5058	27,500	.5408	34,000	.5818	42,000	159.30	266.4
6	162.02	26,250.5	.0206170	.6380	28,000	.6820	35,000	.7325	44,000	126.35	211.4
7	144.28	20,816.0	.0163490	.8044	29,000	.8600	36,000	.9235	46,000	100.21	167.6
8	128.49	16,509.0	.0129660	1.6340	30,000	1.1050	37,000	1.1870	48,000	79.46	133.2
9	114.43	13,094.0	.0102840	1.2780	32,000	1.3670	39,000	1.4680	50,000	62.99	105.4
10	101.89	10,381.0	.0081532	1.6130	33,000	1.7240	40,000	1.8520	51,000	48.71	83.6
11	90.74	8,234.0	.0064670	2.0330	35,000	2.1730	41,000	2.3350	53,000	39.63	66.3
12	80.81	6,529.9	.0051286	2.5650	39,000	2.7410	42,000	3.0840	55,000	31.43	52.6
13	71.96	5,178.4	.0040671	3.2330		3.4560		3.7120		24.83	
14	64.08	4,106.8	.0031469	4.1790		4.4670		4.7980		19.76	

TABLE V

TABLE OF RESISTANCES OF PURE ALUMINUM WIRE*

Am. Gauge, B. & S. No.	Resistance at 75° F.			
	R Ohms 1,000 Feet	Ohms per Mile	Feet per Ohm	Ohms per Pound
0000	.08177	.43172	12,229.8	.00042714
000	.10310	.54440	9,699.00	.00067022
00	.13001	.68645	7,692.00	.0010812
0	.16385	.86515	6,245.40	.0016739
1	.20672	1.09150	4,637.35	.0027272
2	.26077	1.37637	3,836.22	.0043441
3	.32872	1.73570	3,036.12	.0069057
4	.41448	2.18850	2,412.60	.010977
5	.52268	2.75970	1,913.22	.017456
6	.65910	3.48020	1,517.22	.027758
7	.83118	4.38850	1,203.12	.044138
8	1.06802	5.53550	964.180	.070179
9	1.32135	6.97670	756.780	.11156
10	1.66667	8.80000	600.000	.17467
11	2.10120	11.0947	475.908	.28211
12	2.64970	13.9900	377.412	.44856
13	3.34120	17.6420	299.298	.71478
14	4.31800	22.8000	231.582	1.1623
15	5.19170	27.4620	192.612	1.7600
16	6.69850	35.3680	149.286	2.8667
17	8.44720	44.6020	118.380	4.5588
18	10.6518	56.2420	93.8820	7.2490
19	13.8148	72.9420	72.3840	12.192
20	16.9380	89.4300	59.0406	18.328
21	21.3580	112.767	46.8222	29.142
22	26.9200	142.138	37.1466	46.316
23	33.9620	179.320	29.4522	73.686
24	42.8250	226.120	23.3508	117.17
25	54.0000	285.120	18.5184	186.28
26	68.1130	359.650	14.6814	296.32
27	85.8650	453.370	11.6460	485.56
28	108.277	571.700	9.2358	749.02
29	136.535	720.900	7.3242	1,191.0
30	172.170	908.980	5.8087	1,893.9
31	212.120	1,119.98	4.7144	2,941.5
32	273.970	1,445.45	3.6528	4,788.9
33	345.130	1,822.30	2.8974	7,610.7
34	435.380	2,298.80	2.2969	12,109.
35	548.920	2,898.20	1.8218	19,251.
36	692.070	3,654.20	1.4449	30,600.
37	872.930	4,609.20	1.1456	48,661.
38	1,100.62	5,811.20	.9086	76,658.
39	1,387.47	7,325.80	.7207	121,881.
40	1,749.50	9,236.80	.5716	193,835.

*Calculated on the basis of Matthiessen's standard.

TABLE VI

COMPARISON OF PROPERTIES OF COPPER AND ALUMINUM

	Aluminum	Copper
Conductivity (for equal sizes)	.54 to .63	1
Weight (for equal sizes)	.33	1
Weight (for equal length and resistance)	.48	1
Price, aluminum 29c.; copper 16c. (bare line wire)	1.81	1
Price (equal resistance and length, bare line wire)	.868	1
Temperature coefficient, degree F.	.002138	.002155
Resistance of mil-foot (20° C.)	18.73	10.05
Specific gravity	2.5 to 2.68	8.89 to 8.93
Breaking strength (equal sizes)	1	1
Tensile strength (pounds per square inch, hard drawn)	40,000	60,000
Coefficient of expansion, degree F.	.0000231	.0000093

IRON WIRE

8. **Iron wire** is used largely for telegraph and telephone work, but it is seldom employed in connection with electric transmission because of its high resistance. The approximate value of the resistance per mile of a good quality of iron wire may be determined by the formula

$$R = \frac{360{,}000}{d^2} \qquad (1)$$

where d = diameter of wire in mils.

9. For **steel wire**, which is often used in place of iron wire, this formula becomes approximately

$$R = \frac{470{,}000}{d^2} \qquad (2)$$

The various grades of iron wire on the market are termed "Extra Best Best," "Best Best," and "Best"; the resistances of the different grades are shown in Table VII.

TABLE VII

DIMENSIONS AND RESISTANCE OF IRON WIRE

Number B. W. G.	Diameter in Mils = d	Area in Circular Mils = d^2	Weight Pounds		Breaking Strength Pounds		Resistance per Mile at 68° F.		
			1,000 Feet	1 Mile	Iron	Steel	E. B. B.	B. B.	Steel
0	340	115,600	304.0	1,607	4,821	9,079	2.93	3.42	4.05
1	300	90,000	237.0	1,251	3,753	7,068	3.76	4.40	5.20
2	284	80,656	212.0	1,121	3,363	6,335	4.19	4.91	5.80
3	259	67,081	177.0	932	2,796	5,268	5.04	5.90	6.97
4	238	56,644	149.0	787	2,361	4,449	5.97	6.99	8.26
5	220	48,400	127.0	673	2,019	3,801	4.99	8.18	9.66
6	203	41,209	109.0	573	1,719	3,237	8.21	9.60	11.35
7	180	32,400	85.0	450	1,350	2,545	10.44	12.21	14.43
8	165	27,225	72.0	378	1,134	2,138	12.42	14.53	17.18
9	148	21,904	58.0	305	915	1,720	15.44	18.06	21.35
10	134	17,956	47.0	250	750	1,410	18.83	22.04	26.04
11	120	14,400	38.0	200	600	1,131	23.48	27.48	32.47
12	109	11,881	31.0	165	495	933	28.46	33.30	39.36
13	95	9,025	24.0	125	375	709	37.47	43.85	51.82
14	83	6,889	18.0	96	288	541	29.08	57.44	67.88
15	72	5,184	13.7	72	216	407	65.23	76.33	90.21
16	65	4,225	11.1	59	177	332	80.03	93.66	110.70
17	58	3,364	8.9	47	141	264	100.50	120.40	139.00
18	49	2,401	6.3	33	99	189	140.80	164.80	194.80

GERMAN-SILVER WIRE

10. German-silver wire is used principally in resistance boxes or electrical instruments where a high resistance is required. The resistance of this wire varies greatly according to the materials and methods of manufacture used. It is an alloy of copper, nickel, and zinc, and has a resistance anywhere from 18 to 28 times that of copper. Its resistance changes only to a small extent with changes in temperature, a feature of value in connection with rheostats and resistance boxes.

Table VIII gives some of the properties of German-silver wire containing 18 or 30 per cent. of nickel.

TABLE VIII

GERMAN-SILVER WIRE

(*Roebling's*)

Number B. & S. Gauge	Resistance per 1,000 Feet International Ohms		Maximum Current Carrying Capacity in Amperes
	18-Per-Cent. Wire	30-Per-Cent. Wire	18-Per-Cent. Wire
6	7.20	11.21	
7	9.12	14.18	
8	11.54	17.95	
9	14.55	22.63	
10	18.18	28.28	8.5
11	22.84	35.53	5.4
12	28.81	44.82	4.6
13	36.48	56.75	3.8
14	46.17	71.82	3.2
15	58.21	90.55	2.7
16	72.72	113.12	2.3
17	93.40	145.29	1.9
18	118.20	183.87	1.65
19	145.94	227.02	1.21
20	184.68	287.28	.99
21	232.92	362.32	.88
22	295.38	459.48	.66
23	370.26	575.96	.55
24	468.18	728.28	.488
25	590.22	918.12	.434
26	748.08	1,163.68	.385
27	937.98	1,459.08	.343
28	1,191.24	1,853.04	
29	1,481.22	2,304.12	
30	1,891.8	2,942.8	
31	2,388.6	3,715.6	
32	2,955.6	4,597.6	
33	3,751.2	5,835.2	
34	4,764.6	7,411.6	
35	6,031.8	9,382.8	
36	7,565.4	11,768.4	

OVERHEAD CONSTRUCTION

POLES

11. Selection of Poles.—The poles used to the greatest extent in this country are of the following kinds of wood: Norway pine, chestnut, cypress, and white cedar. The average lives of these, under average conditions, are placed by good authority at the following values: Norway pine, 6 years; chestnut, 15 years; cypress, 12 years, white cedar, 10 years. Cedar poles are undoubtedly used to the greatest extent. Considering their strength, they are light in weight, and, by some authorities, are considered the most durable, when set in the ground, of any American wood suitable for pole purposes. In some of the Western States, California redwood is used for poles.

12. Sizes of Poles.—The best lines in this country use no poles having tops less than 22 inches in circumference. If the poles taper at the usual rate, the specification that a pole shall have a top 22 inches in circumference, or approximately 7 inches in diameter, is usually sufficient, for the diameter at the butt will then be approximately correct, no matter what may be the length of the pole. When a pole line has to carry but a few small wires, it is not necessary to have them as large as 7 inches at the top, and poles with a 5-inch top will answer every purpose. For long-distance transmission work, only the most substantial line construction is allowable, because every precaution must be taken to make the service continuous. Long transmission lines usually have to carry heavy wires, and moreover they are often in very exposed localities; for this class of work, therefore, specially heavy poles are used. The length of poles used in any given case is fixed by several considerations. It will

depend to some extent on the number of cross-arms to be accommodated, but more frequently the length is determined by the location of the pole. In any given transmission line it is necessary to use a number of different pole lengths and select the poles so that the tops will be graded, thus avoiding ups and downs in the wire as much as possible. A poorly graded line requires a greater length of wire than a well graded one, and this is objectionable not only on account of the extra cost of the wire, but also because of the larger line loss due to the larger resistance. Table IX shows the size of poles used on the Bay Counties high-tension transmission

TABLE IX

DIMENSIONS OF POLES

Height Feet	Diameter of Top Inches	Diameter of Butt Inches	Depth in Ground Feet
25	8	12	5
40	9	14	6
45	10	15	6½
50	11	16	7½
60	12	18	8

line in California*. Where angles occur in the line, the poles are set 1 foot deeper than shown by the figures in the last column of the table.

13. Spacing of Poles.—Practice varies as to the spacing of poles. Of course, the number and sizes of the wires to be carried are the most important considerations in determining this point, but the climatic conditions, especially with regard to heavy wind and sleet storms, should also be considered. In general, it may be said that the best lines carrying a moderate number of wires use 40 poles to the mile, while for exceptionally heavy lines, the use of 52 poles to the mile, or 1 pole every 100 feet, is not uncommon practice.

*Journal of Electricity, Power, and Gas, Vol. XI, No. 8.

As a general rule, which it is safe to follow in the majority of cases, 35 or 40 poles to the mile should be used. For city work, the poles should be set on an average not farther apart than 125 feet.

CROSS-ARMS

14. The **cross-arms** should be made of well-seasoned, straight-grained Norway pine, yellow pine, or creosoted white pine. Cross-arms are made in standard sizes, the

FIG. 4

length of the arm depending on the number of pins it is intended to hold. The standard cross-arm is $3\frac{1}{4}$ inches by $4\frac{1}{4}$ inches, and varies in length usually from 3 to 8 feet. They are usually bored for $1\frac{1}{2}$-inch pins and provided with holes for two $\frac{1}{2}$-inch bolts. The arms are generally braced by flat iron braces, about $1\frac{1}{4}$ inches wide by $\frac{1}{4}$ to $\frac{3}{8}$ inch thick. These braces are shown in Fig. 4, which gives a view of an ordinary pole top provided with two 4-pin cross-arms. This pole top represents the style of construction suitable for fairly light work, such as is used for local light and

power distribution. For long transmission lines, heavier cross-arms are used. For example, those used by the Standard Company, of California, on a line designed to handle current at 60,000 volts, are 5¾ inches by 5¾ inches, and the holes for the pins are 42 inches apart, this wide distance between the wires being necessary on account of the high voltage. The older Niagara line used cross-arms 4 inches by 6 inches, and the later line 5 inches by 6 inches.

15. Fig. 5 shows the pole top used on the first Niagara transmission line. It was designed to accommodate twelve

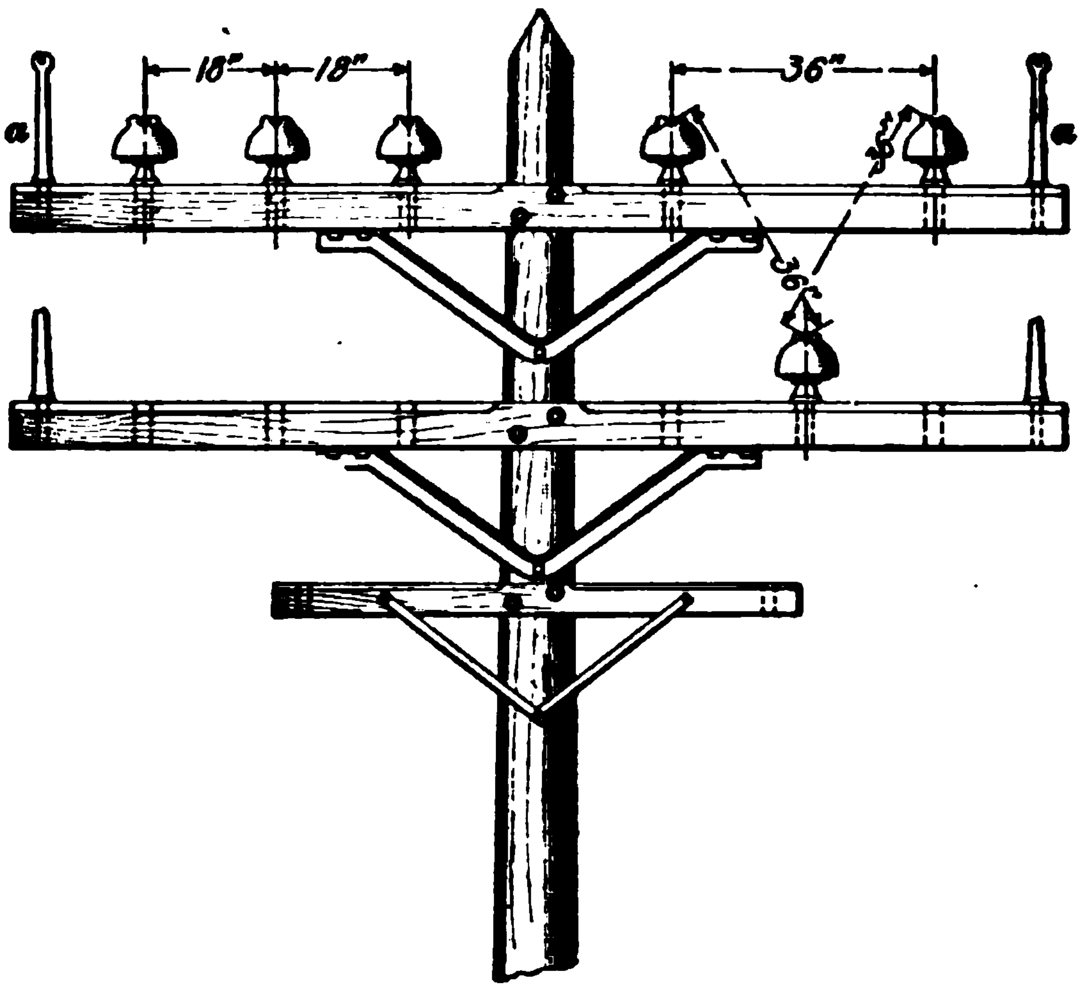


Fig. 5

transmission wires, the insulators being placed side by side on the cross-arms as shown in the left-hand half of the figure. It was found that this arrangement did not work well because it was an easy matter to start short circuits between the wires, and the arc thus started traveled along the line wires until the power was shut off. By adopting the triangular arrangement shown at the right, the distance between the wires was doubled and all three wires made equidistant from each other. The apex of the triangle formed by the wires was placed downwards, as this arrangement

makes it more difficult to lodge sticks or wires across the circuit than if the single wire is placed on the top arm with the other two beneath it, though the latter arrangement is used quite often. The Niagara line is designed to operate at 20,000 volts. The supports *a*, *a* at each end of the cross-arms were intended to hold barb wire that was grounded at regular intervals in order to conduct off lightning discharges. The barb wire was also intended to act to a certain extent as a guard wire to prevent articles from falling on the line. It was found, however, that sleet and snow caused these guard wires to break and fall across the lines,

FIG. 6

FIG. 7

thus giving rise to so much trouble that they were finally removed. Barb wire is nevertheless used successfully in connection with a number of transmission plants, and affords an efficient protection against lightning, but it is necessary to use wire that is heavy enough to stand the strains put on it. Ordinary light barb wire as used for fences is not heavy enough for work where it has only one support in, say, every 100 feet, as is the case on a pole line. Another method that is sometimes used for arranging two three-phase circuits is to use three cross-arms with two wires on each cross-arm, the pins being so placed that the wires come at the corners of a regular hexagon.

PINS

16. One style of pin by which insulators are mounted on cross-arms is shown in Fig. 6. This shows the ordinary pin used for light lines; pins used for heavy long-distance lines are considerably larger and stronger. They may be made of locust, chestnut, or oak (the woods being preferred in the order named), and are turned with a coarse thread on the end on which the insulator is to be secured; the shank *K* is 1½ inches in diameter.

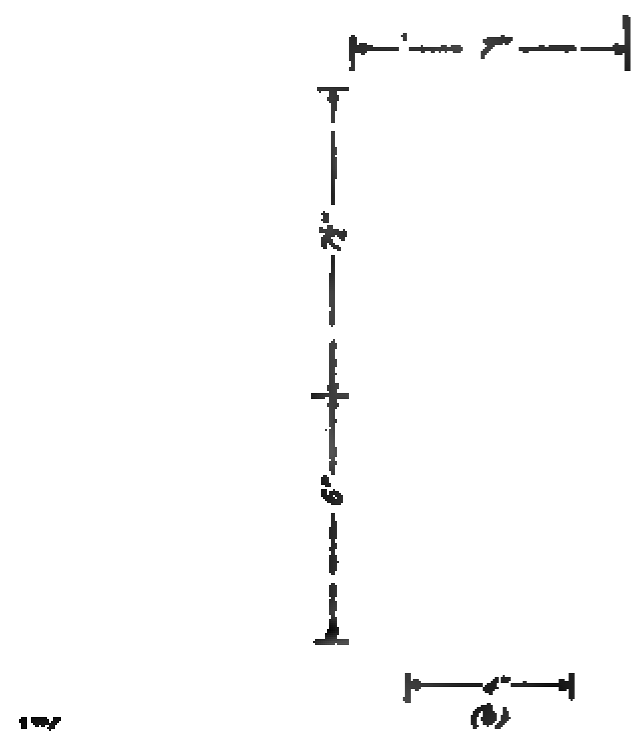


FIG. 8 FIG. 9

The pin should be secured in the hole by driving a nail through the arm and the shank. This renders it difficult to extract the shank of the pin in case a new one is required; but, on the other hand, it prevents the pin pulling out, which sometimes occurs when this precaution is not taken. For heavy lines, pins having an iron bolt passing through them are sometimes used. Fig. 7 shows a pin of this kind, designed by F. Locke, with a heavy insulator for carrying a cable in the groove *a*.

In the case of high-tension, long-distance lines, exceptionally strong pins should be used. These are made of wood, because with high pressures any metal is objectionable near the insulator. Fig. 8 shows the style of pin used by the Standard Company previously referred to. These pins are made of blue gum wood (*Eucalyptus*), specially treated with linseed oil to prevent them from absorbing moisture. This pin is also shown in Fig. 14 in connection with the insulator that it supports. Fig. 9 (*a*) and (*b*) shows two styles of pin used on the Niagara transmission lines; (*b*) is the old-style pin, which was found to be too weak; (*a*) shows the heavier pin used on the later line. Note that in (*a*) the hole for the pin does not pass completely through the cross-arm. About 1 inch of wood is left at the bottom, as this is found to greatly strengthen the cross-arm.

FIG. 10

FIG. 11

17. Insulators in this country are usually made of glass, while in Europe porcelain is more commonly used. Porcelain, when new, is a better insulator than glass; but it is more costly, and under the action of cold the glazed surface becomes cracked. When this happens, the moisture soaks into the interior structure, and its insulating quality is greatly impaired. Tests recently made have shown that when newly put up, the insulation resistance of porcelain insulators is from 4 to 8 times better than glass, but that, along railroads and in cities, smoke forms a thin film on each material, so that at the end of a few months their insulating properties are nearly alike. On country roads, away from railroad

tracks, the porcelain insulators maintain a higher insulation than the glass during rain storms, but in fine weather it is not so high. Porcelain has an advantage over glass in that it is not so brittle, and therefore is less likely to break when subjected to mechanical shocks. It does not condense and retain on its surface a thin film of moisture so readily as glass, i. e., it is less hygroscopic. On the other hand, glass insulators are not subject to such an extent as porcelain to the formation of cocoons and cobwebs under them, the transparency of the glass serving to allow sufficient light to pass through the insulator to render it an undesirable abode for spiders and worms. As cocoons, cobwebs, etc. serve to lower the insulation of the line to a great extent, this is an advantage that, in this country, it is not well to overlook.

FIG. 12 FIG. 13

18. Types of Insulators.—For ordinary work with moderate pressures, glass insulators are used. The style of insulator will depend to some extent on the size of wire to be supported. Wires smaller than No. 6 or 8 B. & S. are seldom used for power transmission lines; hence, the glass insulators, as a rule, must be heavier than the kind used for telegraph or telephone work. Fig. 10 shows an insulator, known as the D. G. (deep groove), that is well adapted for ordinary lines. This insulator is so called to distinguish it from those with smaller grooves, such as are used for telephone or telegraph work. It is provided with two petticoats, or flanges, *a*, *b* over which leakage must take place before the current can leak from the wire to the pin. The use of a number of petticoats increases the leakage distance and provides a high insulation; insulators used on high-tension lines are provided with several

petticoats. When heavy cables are used, it is customary to carry them on especially heavy insulators and to tie down the cable on top of the insulator instead of tying it to the side. Fig. 7 shows a common type of such insulator; the cable rests in the groove *a* and is held in place by a tie-wire twisted around the cable and passing under the ears at *b*, *c*. Good quality glass insulators, such as those just described, may be used for any lines where the potential is not over 2,000 or 3,000 volts; for higher pressures, it is necessary to use a larger insulator giving a higher degree of insulation. Fig. 11 shows a Locke insulator of glass that is suitable for any pressure up to 5,000 volts. This insulator is 4½ inches in diameter, and, it will be noted, is provided with three petticoats, thus giving a long leakage distance from the wire to the pin. Fig. 12 shows a still larger insulator; this one is suitable for pressures up to 25,000 volts and is 5½ inches in diameter. For high pressures, porcelain insulators have been largely used; as yet there does not seem to be any settled opinion as to just which is the better, glass or porcelain, for this kind of work, and on some lines using very high pressures the insulators are made partly of porcelain and partly of glass. Fig. 13 shows a type of porcelain insulator used for one of the Niagara-Buffalo transmission lines. These insulators are elliptical, or helmet, shaped and have an eave, or ridge, *a* on each side, the object of which is to run off the water to the end of the

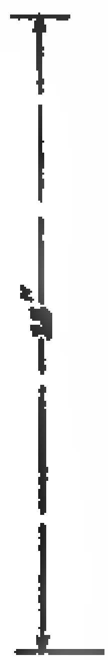


FIG. 14

insulator, where it will drop clear of the cross-arm. Fig. 9 (*a*) shows a section of the later type of insulator used on the Niagara lines, and Fig. 14 shows a style that is used on high-tension lines in California that operate at pressures as high as 40,000 to 60,000 volts; in fact, lines equipped with these insulators have been operated experimentally at 80,000 volts. This insulator is made in two parts, the upper part being of porcelain and the lower of glass. The parts are cemented together by a mixture of sulphur and sharp sand, and the upper part is made of porcelain because moisture does not cling to it as readily as to glass. Glass offers a greater resistance to puncture than porcelain, so that by combining the two materials a very efficient insulator is obtained, and the cost is also reduced materially. The lower part of the pin is covered by a porcelain sleeve that protects the pin from any arc that might tend to strike from the eave of the insulator, and it also protects the pin from the weather. The upper part of the insulator is provided with a ridge around the edge and a projecting lip at one side, so that rain falling on the insulator drips clear of the cross-arm. These insulators are subjected to a test pressure of 120,000 volts for a period of 5 minutes in order to detect any defective insulators before they are put up on the line.

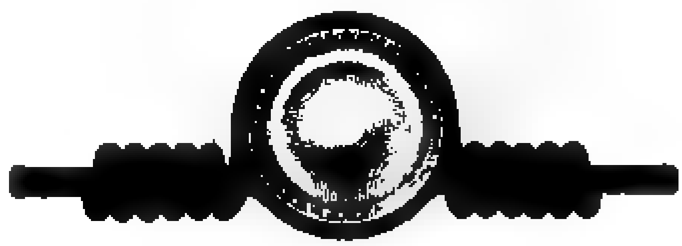


FIG. 15

TYING, SPLICING, ETC.

19. Tying.—Fig. 15 shows the method of tying that is commonly used for small insulators. The tie-wire *a* is from 12 to 16 inches in length and should be insulated to the same extent as the wire to be tied. The line wire is laid in

the groove of the insulator, after which the two ends of the tie-wire, which have been passed half way around the insulator, are wrapped tightly around the wire. Some linemen prefer to wrap one end of the tie-wire over and the other end under the line wire. Fig. 16 shows a method of tying used where the wire lies on top of the insulator as with the Niagara type. Fig. 17 shows the method of tying to the insulator shown in Fig. 14. In this case a No. 4 aluminum tie-wire is used to tie the aluminum cable.

Fig. 16

20. Splicing.—The American wire joint shown in Fig. 18 is generally used for splicing solid wires. The wires are placed side by side and each end wound around the other. All joints should be soldered. The rules of the National Board of Fire Underwriters require that all line joints shall be mechanically and electrically perfect before being soldered; i. e., solder should not be depended on to make the joints strong mechanically or efficient as an electrical conductor. In other words, soldering should always be done simply as a safeguard against any diminution in the electrical conductivity of the joint. Large copper cables are joined either by weaving the strands together and soldering, or by using a copper sleeve into which the ends of the cable are fastened.

Fig. 17

Aluminum wires and cables are very often joined by means of a mechanical coupling, as aluminum is not easily

soldered. Fig. 19 shows an aluminum mechanical joint used on a number of California lines. The cable passes through the sleeves *a*, *a′*, which are provided with right- and left-handed threads, so that they can be drawn tightly together by the threaded sleeve *b*. The ends of the cable are first sawed off square, and after they have been passed through the sleeves, about 1 inch of each cable strand is bent back on itself, and the bunch so formed is forced into the conical part

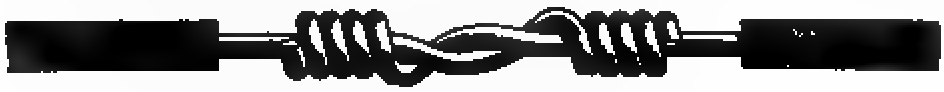


FIG. 18

of the sleeve. A small tapered aluminum plug is then driven into the center, thus wedging the strands firmly, after which the ends are securely screwed together. Another method of using this joint is to turn back on itself about 1½ inches of the core wire of the cable, and after the strands have been forced into place and the joint screwed up tight, the space between the wires is filled with solder. In this case the turned-back wire takes the place of the aluminum wedge and spreads out the cable so that it is impossible for it to pull

FIG. 19

through after the joint is filled with solder. Either method makes a very strong joint of which the resistance is less than a corresponding length of the cable. Aluminum wires are frequently joined by using a long aluminum sleeve or tube having an elliptical cross-section. This sleeve fits the wires snugly when they are slid into it side by side, and after they are in place they are twisted together. This is a good method for splicing solid wires; for stranded cables a sleeve joint is to be preferred.

21. Stringing Aluminum Wire.—Owing to the peculiar physical properties of aluminum wire, special care has to be taken in stringing it; otherwise, breaks in the line will be frequent. Slight impurities in aluminum wire affect both its mechanical and electrical properties to a marked extent. Its coefficient of expansion with increase in temperature is high, and if the stress on the wire is as high as 14,000 to 17,000 pounds per square inch, the wire stretches and takes a permanent set. In stringing the wire, it is therefore important to allow sufficient sag, in accordance with the temperature, so that when the wire contracts it will not be unduly strained. Neglect to do this has resulted in numerous breaks in some of the line wires that have been erected. An aluminum line in warm weather looks as if it had too much sag, but the contraction is so large with decrease in temperature that this slack is very largely taken up in cold weather. Table X, given by the Pittsburg Reduction Company, shows the deflection at the center of the span that should be allowed for various spans together with the tension under which the wire should be put up.

In this table X = deflection in inches at center of span; S = factor by which weight of wire per foot is multiplied to obtain tension.

EXAMPLE.—Suppose a No. 4 aluminum wire is strung on poles 150 feet apart; what sag should be allowed at the center, if the temperature at the time the wire is strung is 30° F.?

SOLUTION.—Opposite the span 150, and under the column for 30°, we find that the deflection X should be 24 in. The weight of No. 4 aluminum wire per mile is 200.9 lb., or the weight per foot is $\frac{200.9}{5,280}$ = .038 lb. Hence, the tension will be $X \times .038 = 1,390 \times .038$ = 52.8 lb. Ans.

22. In stringing the wire it is customary to pull up a number of spans at a time. The deflection is measured by hanging a target on the wire close to the insulator at each end of the span. One form of target consists of an iron strip with cross-marks of different colors corresponding to different deflections. This strip is hung from the wire by

TABLE X

TABLE OF DEFLECTIONS AND TENSIONS FOR ALUMINUM WIRE

X = deflection in inches at center of span; S = factor, which multiply by weight of foot of wire to obtain tension; maximum load = 15,000 pounds per square inch; t = temperature at which wire is strung

	$t = -20°$		$-10°$		0°		10°		20°		30°		40°		50°		60°		70°		80°		90°	
Span	S	X	S	X	S	X	S	X	S	X	S	X	S	X	S	X	S	X	S	X	S	X	S	X
80	12940	$\frac{3}{4}$	1660	$5\frac{3}{4}$	1176	$8\frac{1}{8}$	961	10	833	$11\frac{1}{2}$	781	$12\frac{1}{8}$	680	$14\frac{1}{8}$	630	$15\frac{1}{4}$	589	$16\frac{3}{8}$	555	$17\frac{3}{8}$	527	$18\frac{1}{4}$	502	$19\frac{1}{8}$
100	12940	$1\frac{1}{8}$	2083	$7\frac{1}{4}$	1470	$10\frac{1}{4}$	1202	$12\frac{1}{2}$	1042	$14\frac{3}{8}$	933	16	869	$17\frac{3}{4}$	768	19	735	$20\frac{3}{8}$	695	$21\frac{1}{2}$	658	$22\frac{3}{4}$	628	$23\frac{7}{8}$
120	12940	$1\frac{5}{8}$	2500	$8\frac{5}{8}$	1768	$12\frac{1}{4}$	1400	$15\frac{3}{8}$	1251	$17\frac{1}{4}$	1120	$19\frac{1}{4}$	1022	$21\frac{1}{8}$	946	$22\frac{7}{8}$	885	$24\frac{3}{8}$	835	$25\frac{7}{8}$	792	$27\frac{1}{4}$	755	$28\frac{5}{8}$
150	12940	$2\frac{5}{8}$	3038	$11\frac{1}{8}$	2540	$14\frac{1}{2}$	1788	$18\frac{7}{8}$	1552	$21\frac{3}{4}$	1390	24	1265	$26\frac{5}{8}$	1177	$28\frac{5}{8}$	1060	$30\frac{3}{8}$	1039	$32\frac{1}{2}$	987	$34\frac{1}{4}$	941	$35\frac{7}{8}$
175	12940	$3\frac{1}{2}$	3643	$12\frac{5}{8}$	2576	$17\frac{7}{8}$	2104	$21\frac{3}{4}$	1822	$25\frac{1}{4}$	1630	$28\frac{1}{4}$	1488	$30\frac{1}{8}$	1377	$33\frac{3}{8}$	1279	$35\frac{7}{8}$	1215	$37\frac{3}{4}$	1152	$39\frac{7}{8}$	1099	$41\frac{3}{4}$
200	12940	$4\frac{5}{8}$	4206	$14\frac{1}{4}$	2947	$20\frac{3}{8}$	2403	$24\frac{7}{8}$	2084	$28\frac{3}{4}$	1930	$31\frac{1}{8}$	1672	$35\frac{1}{4}$	1574	$38\frac{1}{4}$	1473	$40\frac{3}{4}$	1393	43	1316	$45\frac{1}{2}$	1256	$47\frac{3}{4}$

means of a hook, and when the lowest point of wire comes in line with the point corresponding to the deflection called for by the temperature at which the wire is strung, the line is tied to the insulator. The correct deflection is easily

FIG. 20

determined by the lineman sighting from one target to the other while the wire is being pulled up (see Fig. 20). Each line foreman is provided with a thermometer and table of deflections. These refined methods are not necessary in connection with the stringing of copper wire, and if the cost of copper and aluminum were equal, copper would doubtless be used on account of its superior mechanical qualities. However, in many cases quite a large saving can be effected on long lines by using aluminum, and this accounts for its use in connection with this kind of work. Aluminum has not as yet been used to any great extent for underground work. The greater cross-section for a given conductivity is here a decided objection, because it would for a given current capacity make the cables considerably larger than those using copper, and this in turn would call for a larger amount of insulating material. With bare overhead lines these objections have little or no weight.

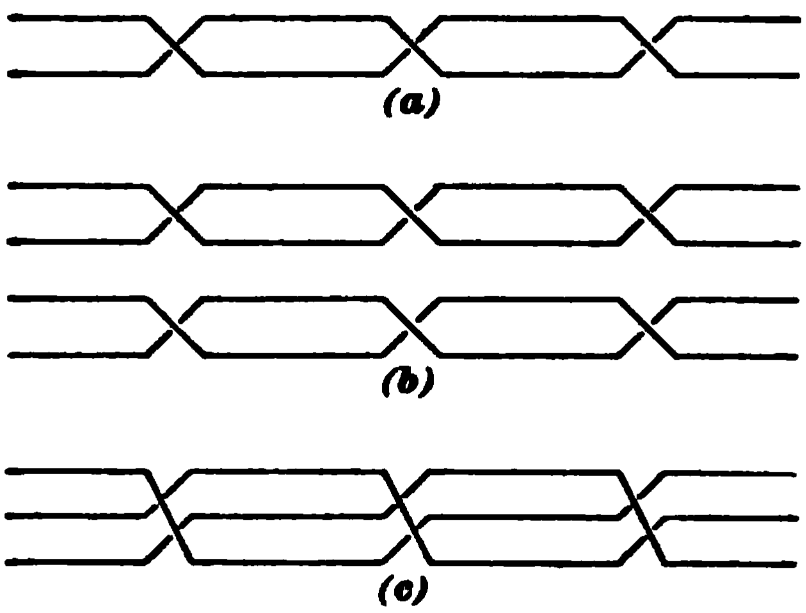


FIG. 21

23. Transposition of Transmission Lines.—When a number of alternating-current transmission lines are run side by side, the alternating magnetic field set up by the currents in one line may set up E. M. F.'s in the other lines,

thus causing unbalancing of the voltage and affecting the line drop. This disturbing action can be avoided by *transposing* or *spiraling* the wires so that the effect produced on one section of the line will be exactly counterbalanced by that produced in another. The most perfect example of spiraling is found in a cable where the conductors that make up the circuit are twisted together and the lines make a complete spiral every few inches. Such a cable has practically no inductive effect on a neighboring cable. Of course, in overhead transmission work, transpositions are not made very numerous because they make the wires harder to trace up in case of trouble and may, on high-pressure work, tend to promote crosses. In fact, some lines that work satisfactorily are not transposed at all. The Niagara lines are transposed in six sections between Niagara Falls and Buffalo, about 23 miles. Practice seems to differ greatly with regard to the frequency with which high-pressure lines should be spiraled. In some cases they are not spiraled at all; in other cases they are spiraled every 2 or 3 miles. Telephone lines, if strung on the same poles with transmission lines should be transposed every fourth or fifth pole, otherwise the telephones may be so noisy as to render conversation very difficult. Fig. 21 (*a*) shows

FIG. 22

the transposition of a single-phase line; (*b*) a two-phase line, and (*c*) a three-phase line. Fig. 22 shows a transposition on a high-tension, three-phase line, each wire being shifted around one pin, or one-third of a turn. Where transpositions

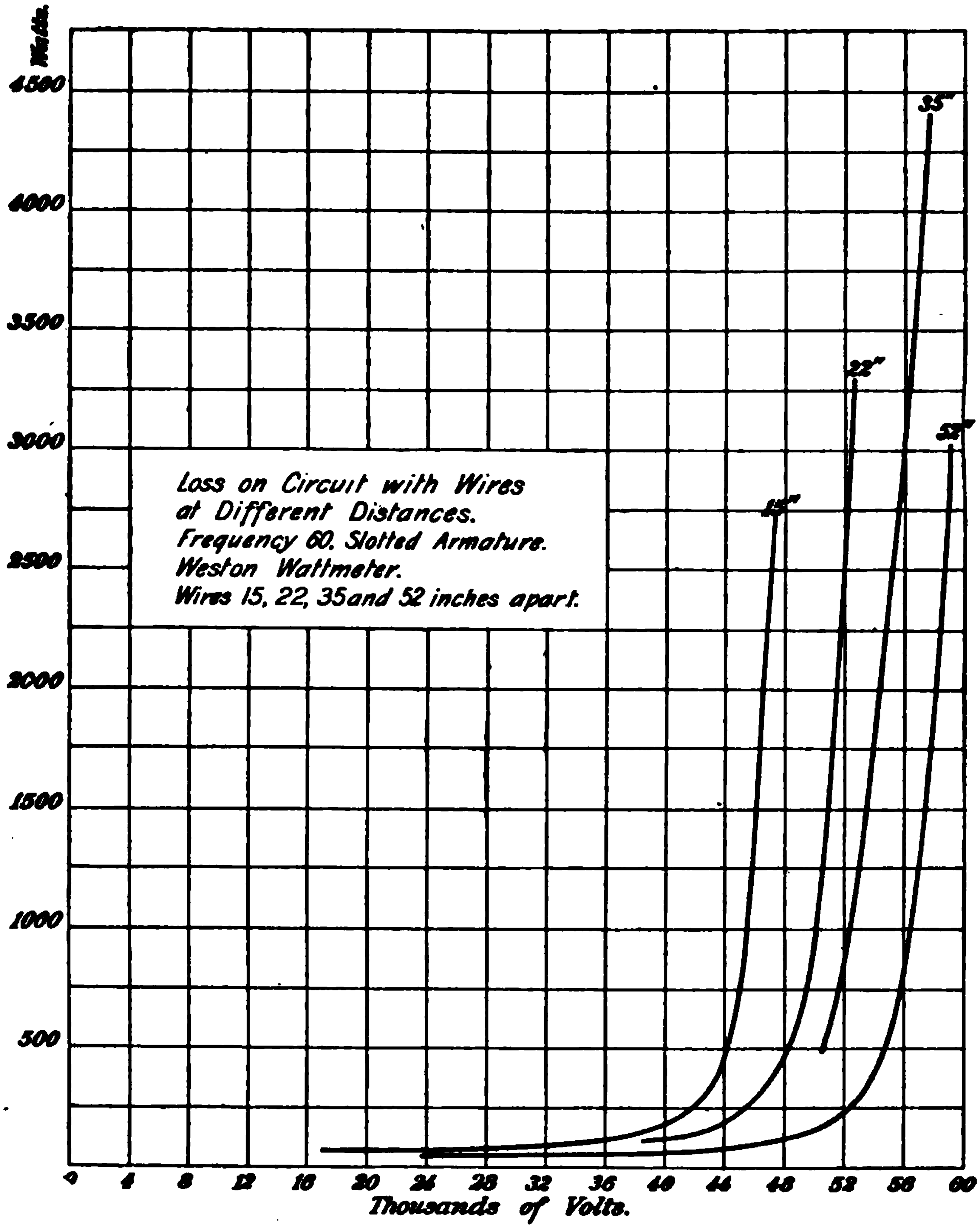


FIG. 23

are made in this way, it is advisable to place the pins on the cross-arms of each pole a little farther apart than the standard distance, so that the lines will not come too close together where they pass each other at the center of the span.

24. Leakage on High-Tension Lines.—On a high-tension line there is always some loss due to leakage, although if the lines be well separated and carefully insulated, this loss may be kept within reasonable limits. The leakage takes place between the wires either directly through the intervening air or over the insulators. When the pressure is raised to a high amount, a brush discharge takes place between the wires and the loss due to this discharge may be considerable, if the wires are not well separated. The curves in Fig. 23 show the results of some tests made by Mr. R. D. Mershon* to determine the relation between the loss, the pressure, and the distance between wires. These tests were made on a line about 2¼ miles in length. It is seen that there is a certain pressure, for each distance between wires, beyond which the loss increases very rapidly and that the nearer the wires are together, the lower the pressure at which the curves begin to rise rapidly. The loss by leakage at the insulators, of course, depends to a considerable extent on the design of the insulator, and also on its condition, i. e., whether wet or dry. It is difficult, therefore, to state very definitely what this loss is, but a number of measurements show that it is in the neighborhood of 2 watts per insulator for lines operated at 25,000 volts, and does not exceed 4 watts with a pressure as high as 44,000 volts.

*Transactions American Institute of Electrical Engineers, Vol. XV.

UNDERGROUND CONSTRUCTION

25. In cities, it is necessary to place the wires underground, especially in the business districts. The best way to do this is to provide a regular tunnel, or *subway*, in which the various wires, or cables, can be placed and which will be large enough to allow a man to walk through for inspection or repair. This method is, however, very expensive and can only be used in a few very large cities. Another method is to use *conduits* through which to run the cables. These conduits usually consist of tubes of some kind that are buried in the ground and thus provide ducts into which the cables may be drawn. The ducts terminate in *manholes* usually placed at street intersections, by which access may be had to the cables and from which they may be drawn into or out of the ducts. A third method and one that has been largely used in cities for distributing current for lighting purposes, is to bury tubes containing insulated conductors in the ground. In this system the conductors cannot be withdrawn, as in the conduit system, and there is a separate tube for each set of conductors. The Edison tube system belongs to this variety, and a very large amount of lighting and power distribution on the three-wire, low-pressure system has been carried out by using underground conductors of this kind.

CONDUITS

26. A large variety of **conduits** are in use, and it has not been definitely settled as yet just which type is the best; but the following will serve to give an idea as to some of the more common forms that have stood the test of actual work and are in extended use.

27. Creosoted-Wood Conduit.—A form of conduit that was at one time largely used is composed of sections

of wooden tubing, the fiber of the wood being impregnated with creosote, in order to prevent its decay. This form of conduit is commonly known as **pump-log conduit.** A section of this conduit is shown in Fig. 24; the ends are doweled in order to preserve the proper alinement in joining. These sections are usually 8 feet in length, and have circular holes through their centers from $1\frac{1}{2}$ to 3 inches in diameter, according to the size of cable to be drawn in. The external cross-section is square and $4\frac{1}{2}$ inches on the side, in the case of a tube having a 3-inch internal diameter. Such a conduit as this, if properly impregnated with creosote, will probably have a life of from 15 to 20 years, and perhaps much longer, this point being one concerning which there is considerable argument and which, probably, time alone will decide. In some cases, difficulty has been experienced with creosoted-wood conduits on account of the creosote attacking the lead covering of the cables.

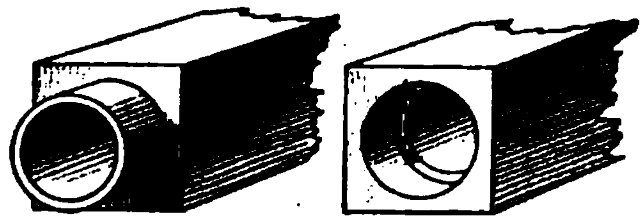


FIG. 24

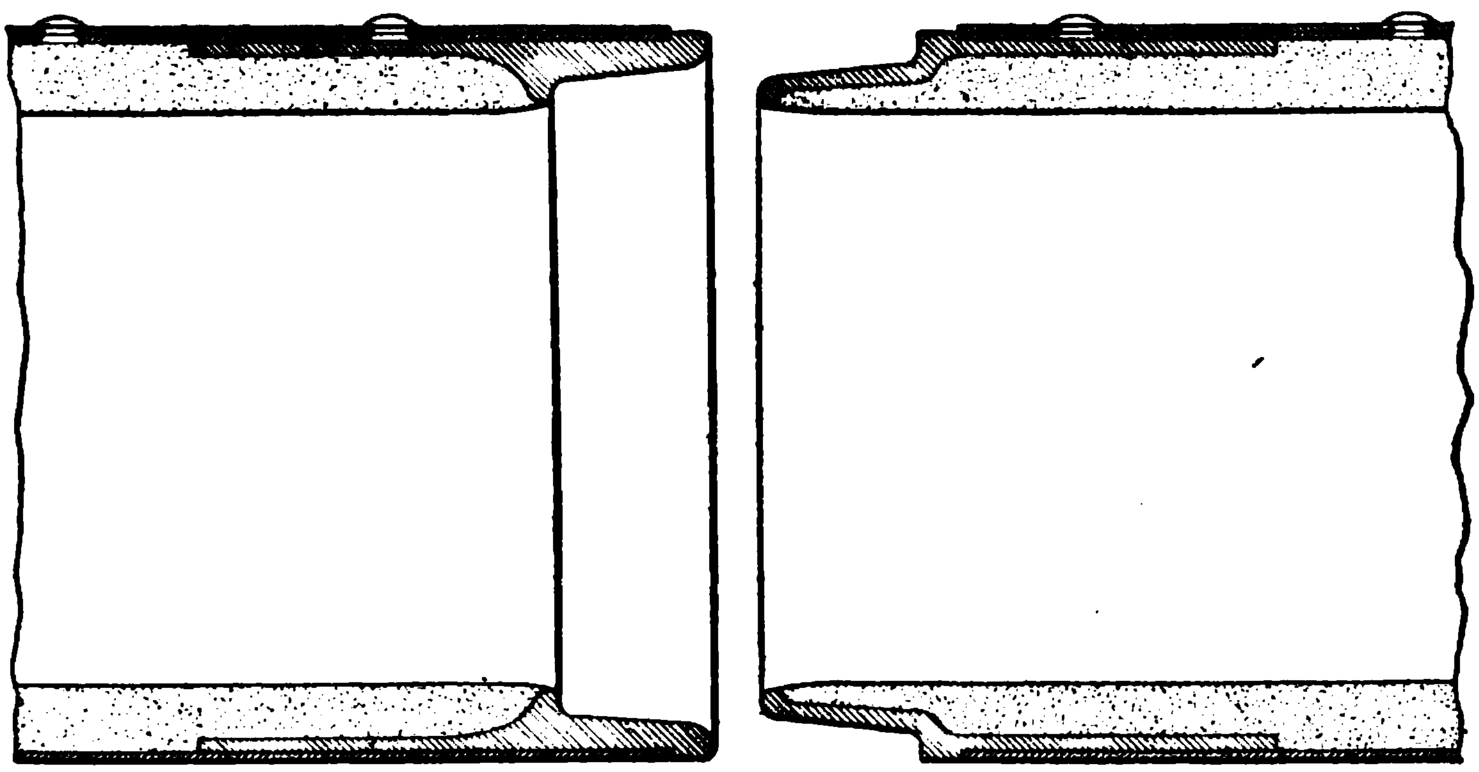


FIG. 25

28. Cement-Lined Pipe Conduit.—This conduit is made by the National Conduit and Cable Company. The sections shown in Fig. 25 are usually 8 feet long and are

made as follows: A tube is made of thin wrought iron, No. 26 B. W. G., .018 inch thick, and securely held by rivets 2 inches apart. The tube is then lined with a wall of Rosendale cement $\frac{5}{8}$ inch thick, the inner surface of which is polished while drying, so as to form a perfectly smooth tube. This tubing comes in three sizes, each having a length of 8 feet and internal diameters of 2, $2\frac{1}{2}$, and 3 inches, the latter being the standard size. Each end is provided with a cast-iron beveled socket joint, by the use of which perfect alinement may be obtained by merely butting the ends together. These beveled socket joints also allow of slight bends being made in the line of conduit as it is being laid.

FIG. 26

29. Vitrified-Clay or Terra-Cotta Conduit.—A form of conduit that is probably used in good construction work to a greater extent than any other is made of vitrified clay. This material has the advantage of being absolutely proof against all chemical action, and unless destroyed by mechanical means will last for ages. Besides this, its insulating properties are high and it is comparatively cheap and easily laid.

FIG. 27

Clay, or terra-cotta conduits are made in two general forms—multiple duct and single duct. Of the former type the most common is the 4-duct, two sections of which

are shown in cross-section in Fig. 26. They are also made with 2, 3, 4, 6, and 9 ducts.

30. The form of clay conduits now most commonly used is the single duct shown in Fig. 27; this is usually made in 18-inch lengths, has an internal diameter of from 3 to $3\frac{1}{4}$ inches, and is $4\frac{5}{8}$ inches square outside. This duct has a

FIG. 28

great advantage over the multiple-duct sections in the greater ease of handling and also in the fact that it is much less liable to become warped or crooked in the process of burning during its manufacture than the larger and more complicated forms. Like the cement-lined pipe, it is laid on a bed of concrete,

FIG. 29

cemented together with mortar, and enclosed on all sides and on top by concrete. In laying, a wooden mandrel, such as is shown in Fig. 28, 3 inches in diameter and about 30 inches in length, is used. At one end is provided an eye *a*, which

may be engaged by a hook, in order to draw it through the conduit, while at the other end is secured a rubber gasket *b* having a diameter slightly larger than that of the interior of the duct. One of these mandrels is placed in each duct when the work of laying is begun. As the work progresses, the mandrel is drawn along through the duct by the workmen,

FIG. 30

by means of an iron hook at the end of a rod about 3 feet long, the method of doing this being shown in Fig. 29. By this means, the formation of shoulders on the inner walls of the ducts at the joints is prevented, and any dirt that may have dropped into the duct is also removed. The cylindrical part of the mandrel insures good alinement of

the ducts, thus securing a perfect tube from manhole to manhole.

31. Fig. 29 illustrates the method of laying this conduit, and shows how the joints should be broken in the various layers so as to insure a maximum lateral strength to the structure. All conduits should be laid to such grades that there will be no low points or traps in the conduit that will not drain into the manholes.

FIG. 31

Figs. 30 and 31 show two arrangements of conduit used for distributing power from the Niagara Falls power station.* These are made of clay ducts laid in cement and covered, as shown, with concrete. The arrangement shown in Fig. 30 was used whenever the sewers were low enough to admit of good drainage, because it allowed a more convenient arrangement of cables in the manholes than the grouping shown in Fig. 31. Drainage was provided by the drain tiles *a*, *a*

*L. B. Stillwell, Transactions American Institute of Electrical Engineers, Vol. XVIII.

surrounded by loose gravel. These conduits are arranged so that there is never more than one duct between any duct and the ground, the object being to facilitate the dissipation of heat generated in the cables.

32. Bituminized-Fiber Conduit.—Another kind of conduit that has recently been introduced is made of fibrous material treated with bituminous compound in such a way as to make a hard, dense tube. This conduit is light, strong, impervious to moisture, and has high insulating properties. Joints are made by fitting the lengths together in the same way as the pump-log conduit. Before placing a length in position, the end is dipped in hot pitch, or similar compound, so that when the end is pushed in, a water-tight joint is formed. The ordinary size of this conduit is 3 inches inside diameter and it is made in 7-foot lengths. The wall of the tube is about $\frac{3}{8}$ inch thick. The conduit is usually laid in concrete, as described for the clay conduit, but owing to the nature of the joints it is not necessary to use mandrels if ordinary care is taken.

MANHOLES

33. Manholes form a very important part in cable systems and require careful designing to properly adapt them to the particular conditions to be met. They are usually placed about 400 feet apart, and, if possible, at the intersection of streets. They should be located with a view to making the line of conduit between them as nearly straight as possible. The size of the manhole will depend on the number of ducts that are to be led to it, as well as the number of men that will be required to work in it at one time. Manholes 6 feet square and from 5 to 6 feet high will usually be required for large systems, while for smaller systems, or the outlying portions of large ones, they may be made as small as 4 feet in length, in the direction of the conduit, 3 feet wide and 3 or 4 feet high.

Manholes may be constructed of either concrete or hard-burned brick laid in Portland-cement mortar. The foundation

should consist of a layer of concrete at least 6 inches thick. The walls, if of brick, should be laid in cement mortar, and should, also, be thoroughly plastered on the outside with the same mortar. They should never be less than 8 inches thick, and should be made double this thickness where large manholes are constructed in busy streets. As the brickwork is laid up, the supports for the iron brackets that hold the cables around the sides should be built in. The roof should

Fig. 32

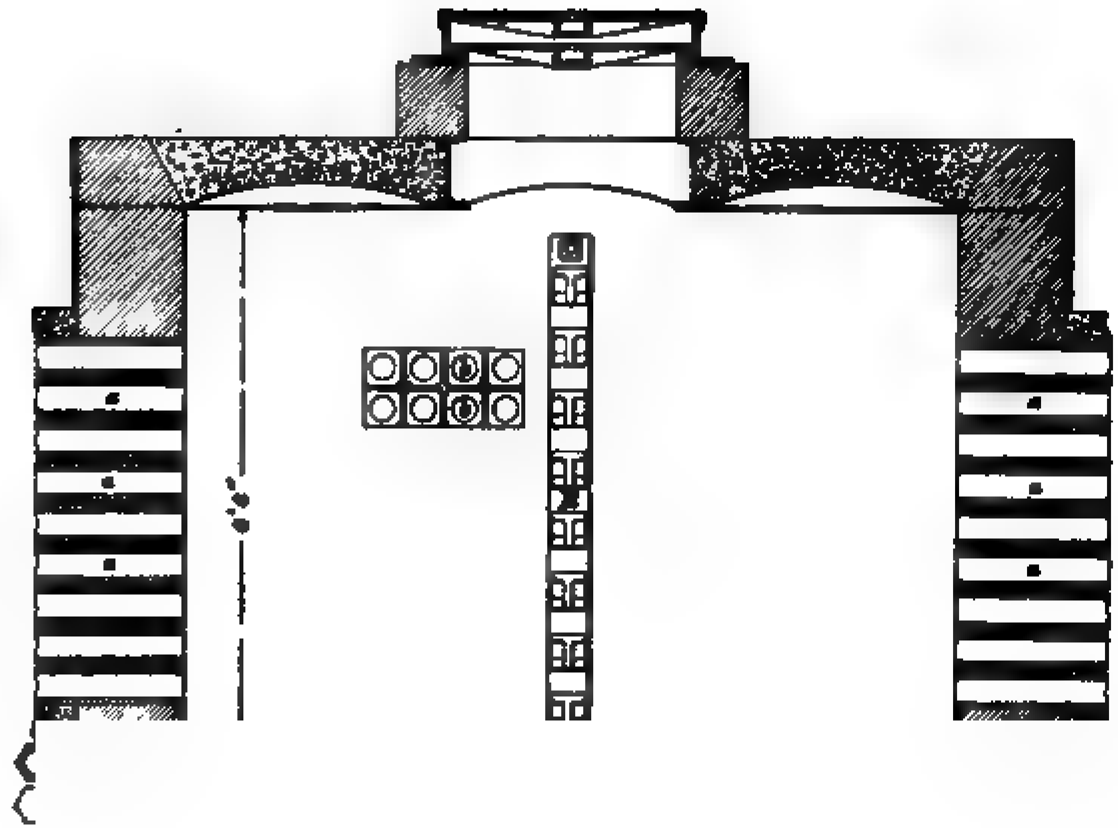
be of either arched brick, concrete, or structural iron, supporting some form of cast-iron manhole cover, of which there are several types on the market.

34. Fig. 32 shows a cross-section of a ventilated manhole well suited for ordinary power-distribution work. It has been found better, on the whole, to provide manholes with ventilated covers and good sewer connections than to close them up tight, as was formerly done. If they are tightly sealed, gases are liable to accumulate and cause explosions. In Fig. 32 the manhole is provided with two

sewer connections, so that in case the bottom one gets clogged up, the water will be able to flow through the side connection instead of backing up into the ducts. Both connections are provided with traps to keep out the sewer gas, and the bottom connection is equipped with a backwater valve to keep water from backing into the manhole. A removable cover is provided at the backwater valve, so that any dirt that accumulates can be cleaned out.

The roof of the manhole is made by laying 3″ × 3″ I beams across the top and filling between them with brick, the whole being covered with a layer of cement. The manhole cover may be either round or rectangular, the round type being preferred. Fig. 33 (*a*) and (*b*) shows two sectional views of the style of manhole used with the conduit shown in Figs. 30 and 31. The roof of this manhole is made of concrete arches supported by the side wall and by two I beams, as shown; *a*, *a*, *a* are the ducts of the main conduit, and *b*, *b* the ducts of the conduit through which the branch lines are taken. The cables pass around the side of the manhole, and are held in place on the racks *R*, *R*. The manhole is provided with a sewer connection at *S*, and the drains that run alongside the conduit also attach to the sewer connection, as shown.

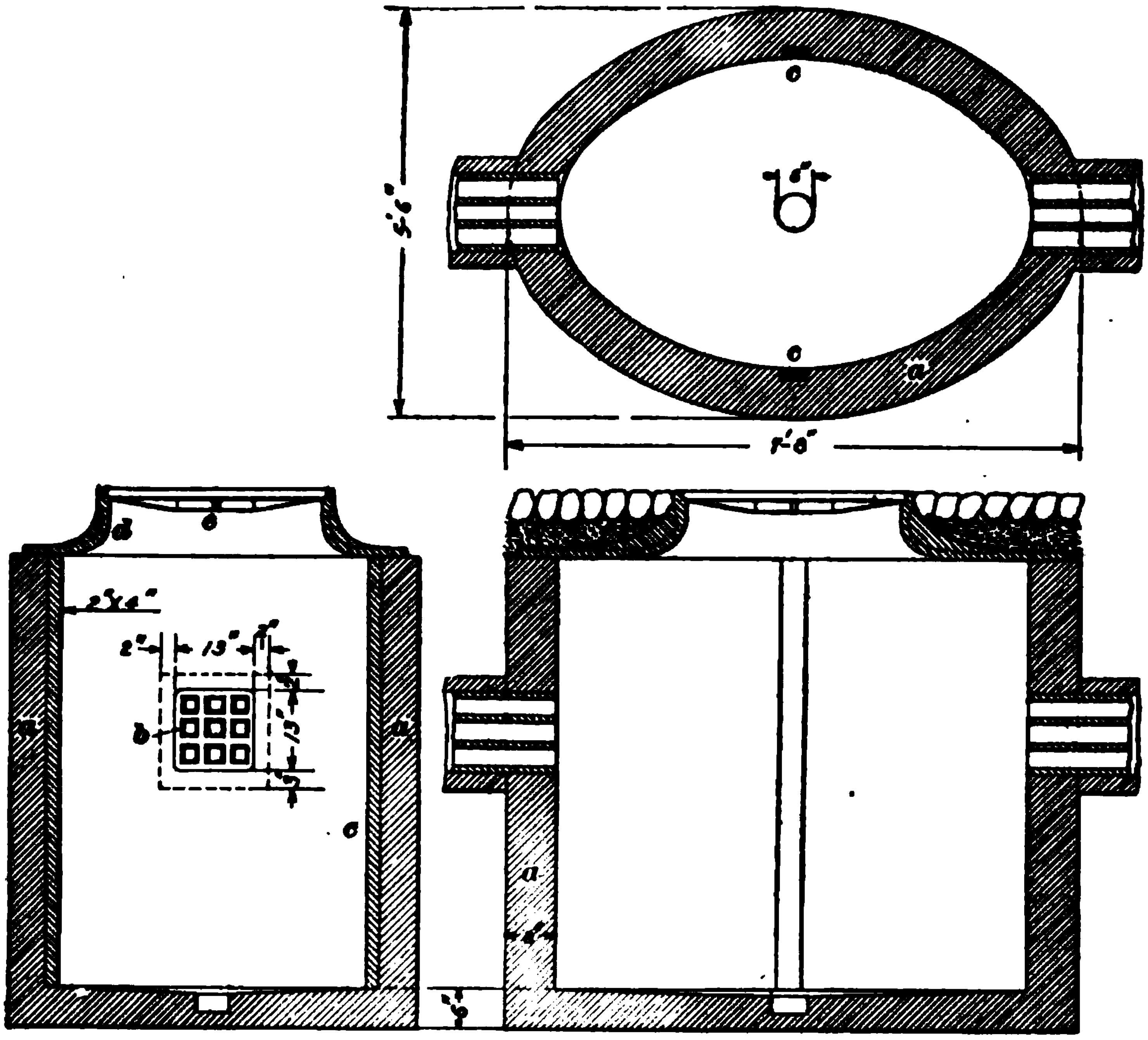
35. Fig. 34 (*a*) shows an elliptical manhole made of concrete. This shape of manhole is becoming popular because it allows the cables to be easily bent to lie against the sides of the manhole. The rectangular corners of a square manhole are practically waste space, because the cables cannot be forced into these corners, or if the attempt is made to force them in, they are almost sure to be damaged. The elliptical form therefore utilizes the material to the best advantage. The main features of the construction are shown by the figure, so that little explanation is necessary. The main part *a* is of concrete, molded in a suitable form, and in this case the conduit *b* is of the 9-duct multiple type. The 2″ × 4″ timbers *c* are built into the concrete to form a base for the cable brackets. This manhole is comparatively small, so



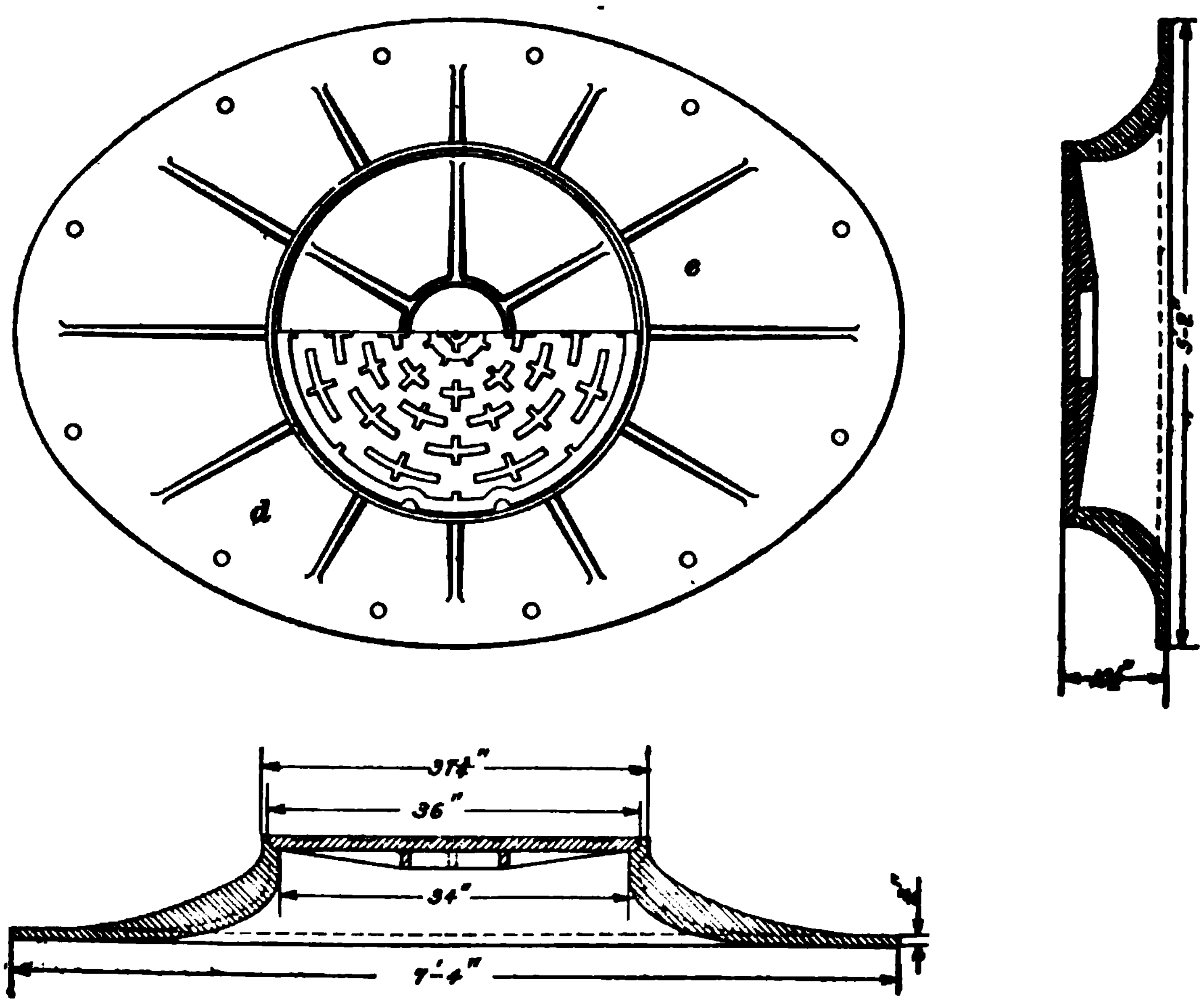
(a)

(b)

FIG. [illegible]



(a)



(b)

FIG. 34

that the holder *d* for the cast-iron cover *e*, forms the roof. This manhole, like nearly all those now constructed, is of the ventilated type. In case manholes are situated above the level of the sewer, the water that accumulates in them is usually removed by means of a water siphon. Fig. 34 (*b*) shows the cast-iron roof and cover.

36. After all work on the conduit and manholes has been completed, the cables are drawn into the ducts. In order to do this, it is necessary to have a wire or rope passing through the duct; this is introduced by the process called **rodding**, which consists in pushing a number of jointed rods into a duct from one manhole until the first rod reaches the other manhole. The rods are joined together by screw connections or bayonet joints, as they are pushed in. When the chain of rods reaches between the two manholes, a rope or wire is attached to one end and pulled through, the rods being disjointed one by one as they reach the second manhole.

The introduction of the wire into the duct may often be greatly facilitated by using, instead of the rods, a steel wire about $\frac{1}{4}$ inch in diameter and provided with a ball about 1 inch in diameter at its end. This wire may be pushed through a smooth duct without trouble for distances up to 500 feet. If an obstruction is found during the rodding that cannot be removed by means of the rods or by water, the distance to the obstruction can readily be measured on the withdrawal of the rod. The conduit should then be opened, the difficulty removed, and the structure repaired. This difficulty, however, should never be met when proper care is taken in laying the conduit.

37. Drawing In.—The process of **drawing in** the cable is illustrated in Fig. 35. The cable reel should be mounted on horses, so as to be free to revolve in such a manner that the cable will unwind from its top. The end of the rope leading through the duct should then be attached to the cable by grips made specially for the purpose or by binding it with iron wire for a distance of 18 inches or 2 feet

from the end. Fig. 35 (*b*) shows a section of a cable grip of iron pipe made to fit the cable snugly. It is fastened to the cable, as shown, by common wood screws, and the piece *d* to which the drawing-in rope is fastened is screwed into the end of the iron pipe. Another form of cable grip is shown

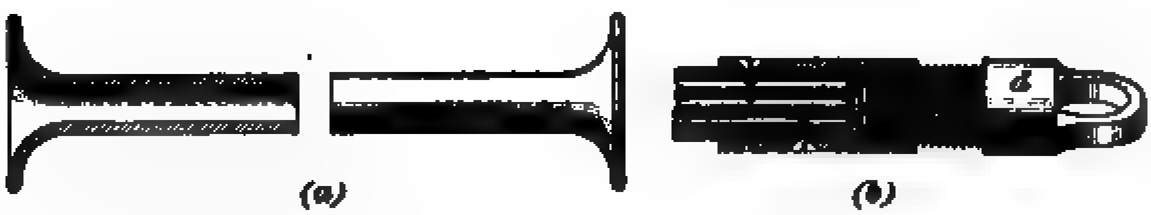


FIG. 35

in Fig. 36. Whenever a hole is made in the end of the cable for fastening the drawing-in rope, the end should be cut off when the cable has been drawn in, the moisture driven out, and the end sealed if a joint is not to be made at once. The other end of the rope is passed over the grooved rollers, arranged on heavy planks mounted in the distant manhole, as shown, and is secured to a capstan or some form of windlass, by which a slow and steady pull may be exerted.

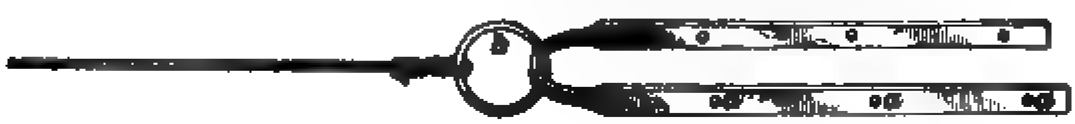


FIG. 36

A man should be stationed in the manhole at which the cable enters to properly guide the cable into the duct, to prevent it from being kinked or unduly strained. It is well to use a special funnel-shaped guide, made of wood or lead, at the entrance of the duct, in order to further insure the cable against injury by the corners of the duct. This guide

is shown in Fig. 35 (*a*). It is sawed longitudinally into two sections, as shown in the left part of Fig. 35 (*a*), where the cable is to continue on through a manhole and where it would therefore be impossible to remove the cylindrical protector were it not sawed in two. Fig. 37 shows another arrangement for drawing in cables. In this case the windlass is arranged vertically in the manhole itself.

DISTRIBUTION FROM MANHOLES

38. Cables.—The construction of the **cables** themselves depends on the kind of service to which they are to be put. Two kinds of insulation are available—rubber and paper. With good rubber insulation, a small puncture in the lead sheath may not impair the insulation for some time, because the rubber is, to a large extent, proof against moisture. On the other hand, paper insulation will be damaged if the lead sheath becomes punctured so as to admit moisture. Paper insulation is, however, cheaper than rubber, and if the cables are carefully installed will give excellent service. Fig. 38 shows a paper-insulated cable designed for 6,600-volt, three-phase transmission. The three conductors are insulated with paper wrapping to a thickness of $\frac{1}{8}$ inch. These three strands are then twisted together and covered with a wrapping of paper $\frac{1}{16}$ inch thick, over which the $\frac{1}{8}$-inch lead covering is forced. The paper is treated with insulating compound and the space between the strands, shown black in the figure, is filled with jute treated with insulating compound.

39. Underground cables have been regularly operated in America at a pressure of 25,000 volts. These cables were made for the St. Croix Power Company, and both paper-insulated and rubber-insulated cables were installed, the construction of the cables being similar to that shown in Fig. 38. The paper insulation on each conductor is $\frac{9}{32}$ inch thick, and the outside paper jacket is $\frac{4}{32}$ inch thick. In the rubber cable, the insulation on each conductor is $\frac{7}{32}$ inch thick, and the jacket surrounding the

conductors is $\frac{5}{32}$ inch thick. The sheath is of lead with 3 per cent. of tin added.

40. Junction Boxes.—In underground electric-power distribution, it is important to have the various parts of the system so arranged that they can be disconnected, if necessary, because faults are liable to develop, and if the various sections can be readily disconnected, it makes the location of the defective portion very much easier to find; also, when

FIG. 37

the defective part is located, it can easily be cut out without interfering with the operation of the remainder of the system. Again, at a manhole or other distribution center, where a number of distribution cables are connected to the main

feeders running to the power station, it is necessary to insert fuses, so that any branch will at once be cut off from the main cables in case of an overload, short circuit, or other defect giving rise to a rush of current. On low-pressure networks, the distribution cables are attached to the main cables, or feeders, by means of *junction boxes*, which are provided with suitable fuse terminals. Junction boxes are made in a

FIG. 39

great many different styles, but they are usually in the form of cast-iron boxes, containing suitable fuse-contact terminals and arranged so that they can be fastened to the side walls or roof of the manhole. These boxes must of course be water-tight.

41. Fig. 39 shows a typical junction box designed for fastening to the side walls or roof; it is known as a *four-way box*, because it accommodates four positive and four negative branch cables; it is designed for use on low-pressure, three-wire work. *A* and *B* are the positive and negative bars, which are made of copper and are well insulated from each other. These bars are connected to the cable terminals through copper fuses *f*, so that in case a short circuit occurs on a line, the fuses will blow and thus prevent damage. The short neutral bar shown in the bottom of the box attaches directly to the cables, because it is not usually considered necessary or even desirable to place a fuse in the neutral. The small wires *p*, *p* are *pressure wires* that run back to the station and there connect to the voltmeter, so that the voltage at the center of distribution, represented by the

junction box, may be determined at any time. These pressure wires are protected by fuses placed in the small fuse receptacles *b*, *b*, *b*. Each pressure wire connects to one side of a cut-out *b* and the other sides connect to the +, −,

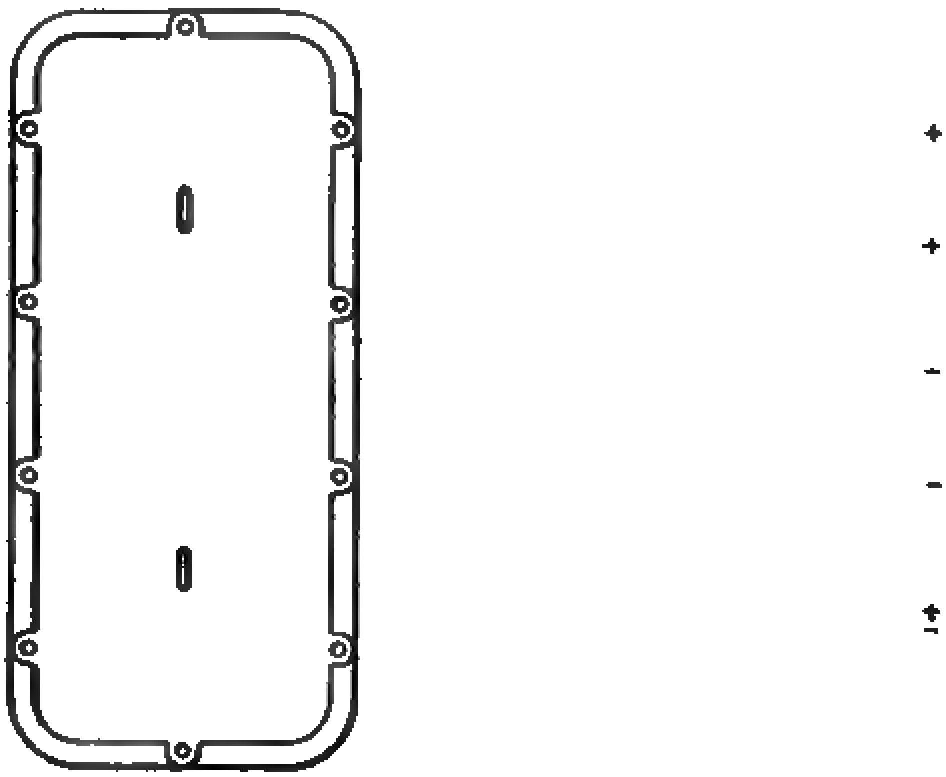


Fig. 39

and neutral bars. The cables pass into the box through water-tight rubber gaskets, and the box is closed by a water-tight cover.

Fig. 40 shows a recent type of junction box made by the General Electric Company. This differs considerably from those of the ordinary type, as it is designed to be placed in the roof of the manhole and access gained to it from the street. In many manholes there is very little room for placing junction boxes on the side walls without interfering with the cables, and moreover manholes are sometimes filled with gas or water so that it is a difficult matter to get at the boxes to replace fuses or disconnect defective cables. Fig. 40 (*a*) is an exterior view of the box and (*b*) shows it

located in a manhole. All cables enter through the bottom, the lead sheath being joined to a nozzle by means of a wiped joint and the nozzle secured against the box by means of a union, as shown, thus making a joint that is gas- and water-tight, yet easily connected or disconnected. Fig. 40 (*c*) shows the arrangement of the fuses. The main cables connect, through fuses, to the castings *a*, *b*, *c* and the branch cables are connected to these through fuses *d*, *e*, etc. The box

(c)

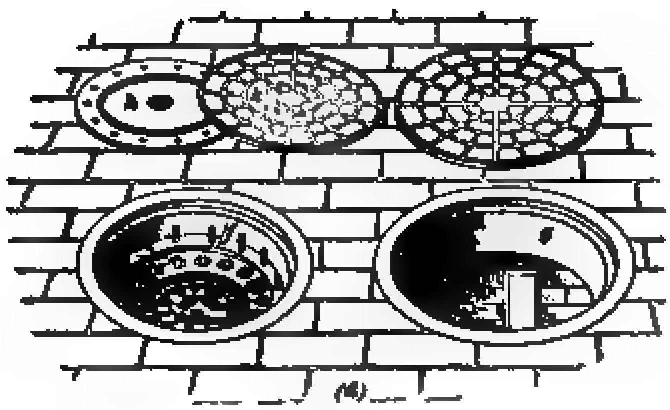


Fig. 40

is intended for a three-wire system and *1*, *2*, *3* are small blocks to which the pressure wires are connected. In Fig. 40 (*d*), the location of the junction box *f*, with reference to the manhole opening *g*, is shown. The junction box is made water-tight by means of the inner cover *h*, which is screwed down against a gasket. After the box is installed, a small hole is made close to the inner cover and opening into the manhole; this prevents any great accumulation of water

between the inner and outer covers, so that there is little tendency for the gasket to leak. The junction box is covered by a loose cover *k* similar to that used for the manhole. If desired, the lower part of the box can be filled with oil, similar to that used in transformers; this is advisable with paper-insulated cables, as the oil will prevent moisture from working its way into the insulation.

42. Service Boxes.—When the conduit system of distribution is used, and where customers have to be supplied, small *handholes* are provided wherever distributing points may be necessary. These are much smaller and shallower than manholes and only run down as far as the conduit. In these handholes a **service box** is placed. Fig. 41 shows

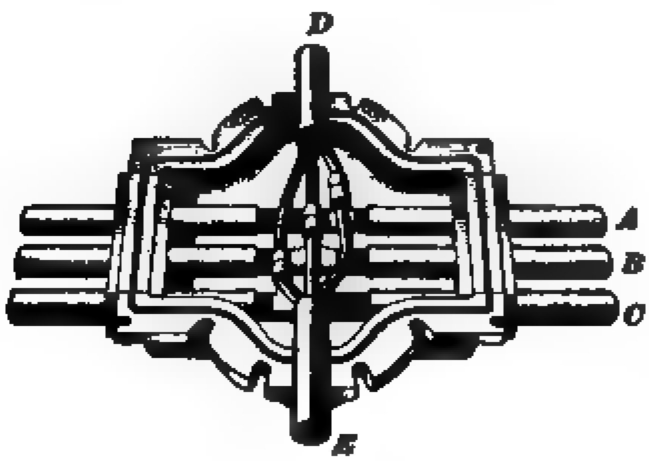


FIG. 41

one style of service box with its cover removed. *A*, *B*, and *C* are the main cables that run straight through the box without being cut. *D*, *E* are the three-wire branch-service cables, or tubes, for supplying current to the buildings. These are attached to the main cables by means of suitable clamps, and after the cover is bolted in position the box is filled with insulating compound. Fig. 42 shows another style of service box for use on the three-wire system. In this four-way box the main cables are fastened to terminals instead of passing straight through. Fig. 43 shows a handhole with its service box arranged for delivering current to overhead conductors. The main feeders, running from manhole to manhole, are placed in the lower tiers of conduits, and the service mains

that run back from the manholes are run in the upper row, so that they will be accessible for the connection of service boxes.

43. Joining Cables.—For low-pressure work, cables are usually joined in the manholes by means of coupling boxes or junction boxes. Sometimes, however, joints must be made without the use of these boxes, in which cases the job must be very carefully done.

First, the soldered end of the cable is cut off and the cable carefully examined for moisture. If a little moisture be present and there is still more than enough room for the joint, it is allowable to cut off another short length. If indications of moisture are still present, heat should be applied to the lead covering, starting from a distance and proceeding along the cable to the end. Thus, the moisture is driven out at the cut. When the use of torches is not allowed on account of gas in the manholes, hot insulating compound, such as boiling paraffin, may be poured over the cable. This process is known as boiling out. To ascertain whether moisture is present, the piece last cut off is stripped of its lead covering and plunged into hot insulating compound. If bubbles rise, moisture is still present.

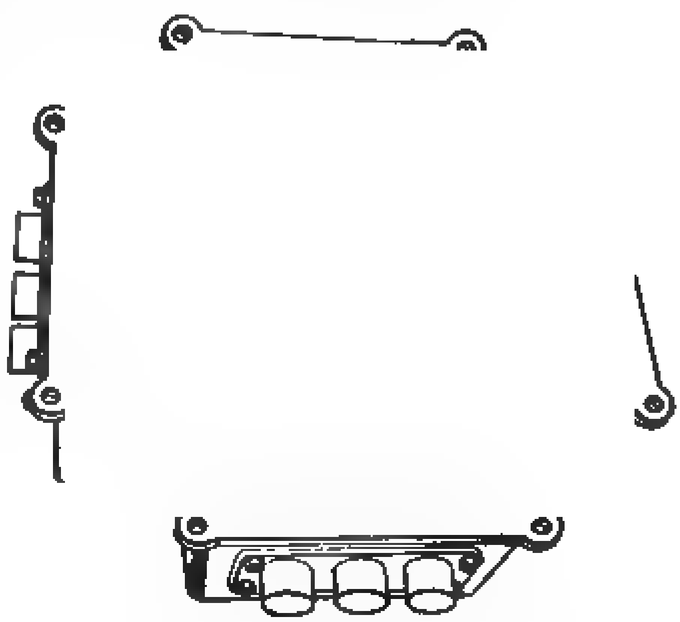


FIG. 42

44. High-Tension Cable Joint.—Fig. 44 shows a typical **high-tension cable joint.** After all moisture has been driven out, the lead sheath is cut off for a suitable distance from each end and the cable insulation is also cut back as indicated. A piece of lead pipe *A* of considerably larger diameter than the cable and a little longer than

the total length of sheath stripped off is then slipped back on the cable. A copper sleeve (*b*) connects the abutting ends of the cable, and is sweated in place with solder worked in through the slot in the top of the sleeve. The sleeve is then covered with tape until it is brought up to a level with the cable insulation and a paper insulating sleeve *c* that has previously been slipped back over the cable insula-

Fig. 43

tion is placed over the joint and held there by a wrapping of string. The lead sleeve is now slipped into place and the ends hammered down around the cable sheath as indicated, and then soldered to the sheath with a plumber's wiped joint. These joints should be very carefully made so that there will be no opportunity for moisture to work into the cable and thus cause a breakdown. Two V-shaped openings are made in the top of the sleeve by cutting the lead and turning it back, as shown in (*c*); through one of these hot insulating compound is poured until the joint is filled. One

of the openings allows the air to pass out while the compound is poured in at the other. In joining high-tension cables, the greatest care must be taken to have the joint perfect in every

FIG. 44

particular. A slight defect may lead to a serious breakdown after the cable has been in use a short time.

EDISON UNDERGROUND-TUBE SYSTEM

45. The **Edison underground-tube system** differs from the conduits previously described in that the conductors are placed in iron tubes that are buried in the ground. The conductors are, therefore, not removable. This arrangement has been used extensively for three-wire 110–220 volt distribution in the larger cities. The conductors themselves are usually in the shape of round copper rods; the main tubes are designed for use on the three-wire system and are, therefore, provided with three rods, as shown in the section in Fig. 45. Each rod is wound with an open spiral of rope that serves to keep the rods separated in case the insulating material in the tubes should become soft. After

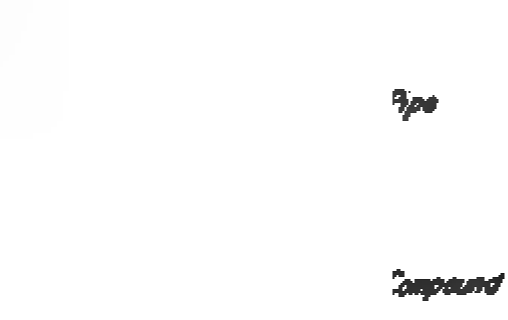


FIG. 45

the rods have been provided with the rope spiral, they are bound together by means of a wrapping of rope and inserted in the iron pipe, the rods projecting for a short distance at each end. The whole tube is then filled with an

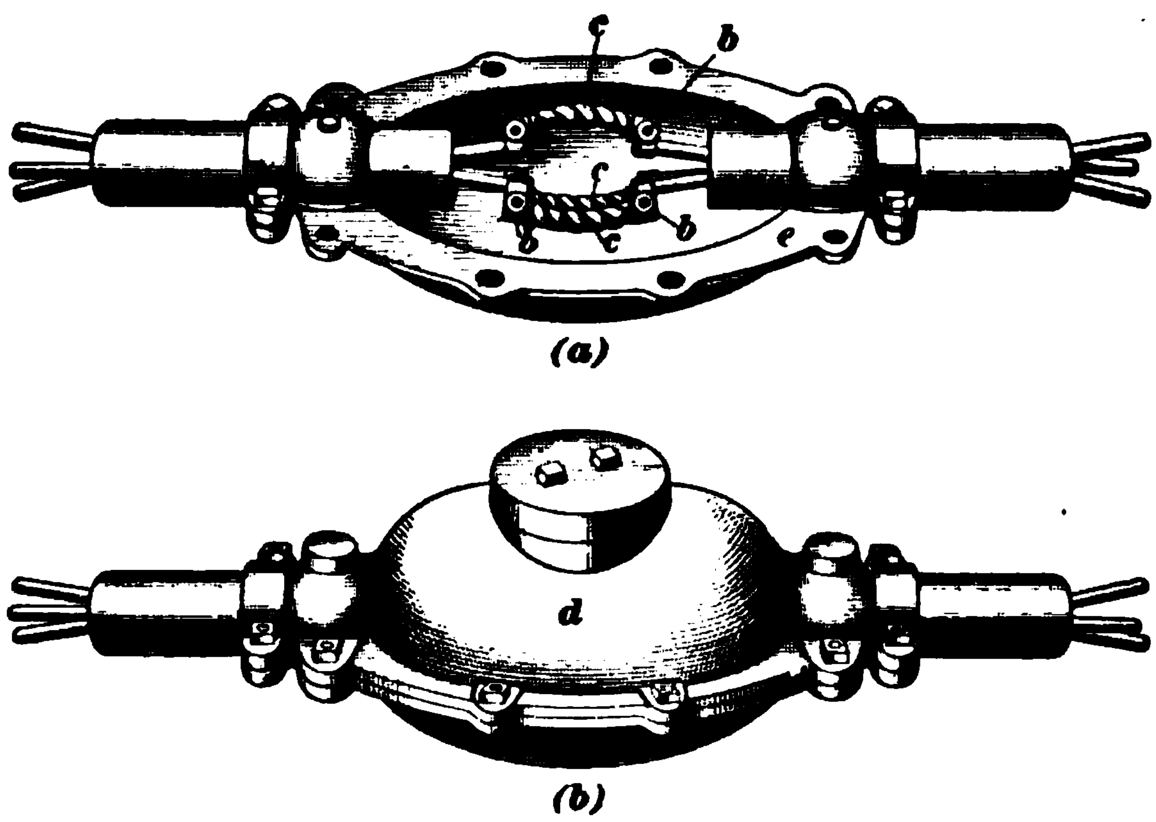


FIG. 46

insulating compound that becomes hard when cold. The tubes are made in 20-foot lengths and are laid in the ground about 30 inches below the surface of the pavement. They are joined together by means of the coupling boxes shown in Fig. 46 (*a*) and (*b*). Fig. 46 (*a*) shows the lower half of the box only, with the main tubes entering each end. The conductors are connected together by means of short, flexible, copper cables *c*, *c*, *c*, provided with lugs *b*, *b*, that fit over the rods and are soldered in place. A cover *d* similar to the lower half *e* is then placed in position and the two securely bolted together by means of flange bolts, as shown in (*b*). After this has been done, melted compound is poured through an opening in the upper casting and the joint is complete. Fig. 47 shows two styles of connectors used for connecting the ends of the rods; (*a*) is a stranded

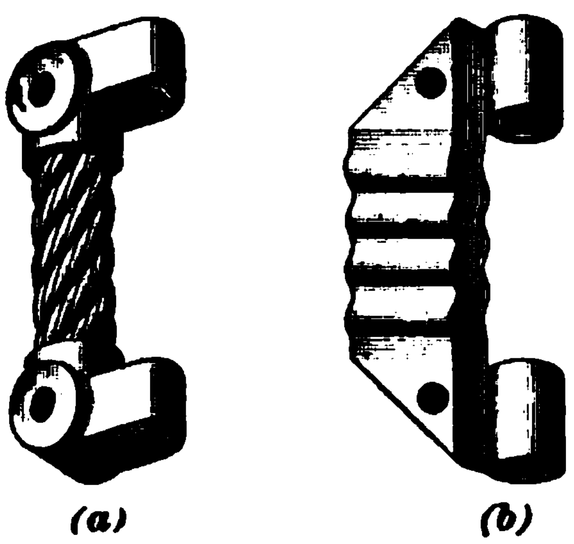


FIG. 47

copper cable with terminals, and (*b*) is a laminated copper connector. Fig. 48 indicates a length of pipe with a coupling.

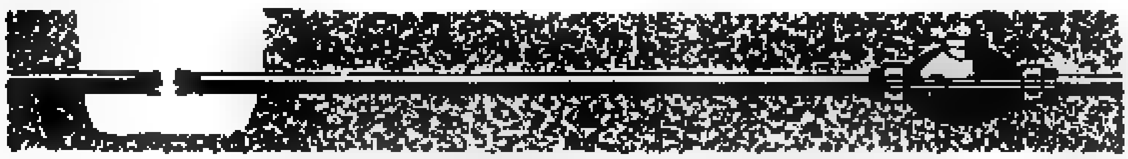


FIG 48

46. Where branches are taken off the mains, T coupling boxes are used, as indicated in Fig. 49. This box, also, is filled with insulating compound that soon becomes hard and prevents the flexible connections from coming in contact with one another. At the centers of distribution (usually a

street intersection) junction boxes are provided; these correspond to the manholes of the conduit system. The main supply wires, or feeders, run from the station to these junction boxes, whence the mains are run to the various districts

where light or power is supplied. Fig. 50 shows one of these junction boxes. The tubes enter at the lower part of the cast-iron box, and the mains are connected to the feeders through fuses that bridge over between the rings shown at the top. These fuses must be proportioned according to the size of the conductor in the tube to which they are

Fig. 50

connected. The allowable carrying capacities of underground tubes and cables have been made the subject of a large number of tests by the manufacturers, who furnish tables giving the limit to which their cables or tubes may be loaded with safety. The junction box shown in Fig. 50 is made water-tight by clamping down the cover by means of the

studs *b*, *b*, and the whole is then covered with a cast-iron plate resting in the groove *c* and coming flush with the street surface.

47. The underground tubes and fittings are rather expensive, but they are comparatively cheap to install, as all that is necessary is to dig a shallow trench and lay the tubes in the ground. This system has the disadvantage that if any trouble occurs it is somewhat awkward to get at

TABLE XI

CARRYING CAPACITY OF UNDERGROUND TUBES

Size of Each Conductor Circular Mils	Maximum Current in Each of Two Conductors
41,000	100
80,000	200
100,000	235
120,000	260
150,000	295
200,000	350
250,000	400
300,000	450
350,000	495
400,000	540
450,000	580
500,000	620

it, as the conductors cannot be pulled out as in a conduit system. When trouble occurs, the usual method of procedure is to dig a hole at one of the couplings and separate the ends. By making a few breaks in this way at different points, the section in which the ground or short circuit is present can soon be located and the defective length of tube removed. Another and quicker method of locating grounds will be described later.

48. The Edison tube system is not now used as largely as it once was for the main distributing lines or feeders. The present practice is to carry the main conductors from the station to the various distributing points in ducts, so that they may be drawn out if necessary. The tube system is, however, well adapted for the distributing mains, and is largely used for this purpose, because it allows service connections to be made easily and cheaply. Table XI gives the cross-section of the rods used in the standard tubes that are now used for distributing mains. Each tube has three conductors of the same size, and the table shows the allowable current when two of the conductors are loaded. If the system is balanced, the third wire will carry but a small current.

TESTS

49. In testing lines or apparatus, it is frequently necessary to make rough tests that will show whether or not circuits are continuous, broken, crossed, grounded, or properly insulated. These tests do not require accurate measurements; they are merely made for the purpose of determining the existence of a faulty condition.

50. **Magneto Testing Set.**—The most common, and probably, all things considered, the most useful, form of testing instrument for rough testing is that consisting of a magneto generator and bell mounted compactly in a box provided with a strap for convenience in carrying.

TESTING LINES FOR FAULTS

51. **Faults** on a line may be of two kinds: the line may be entirely broken, or it may be unbroken but in contact with some other conductor or with the ground. The former fault is termed a *break;* the latter a *cross*, or *ground.* A **break** may be of such a nature as to leave the ends of the conductor entirely insulated, or the wire may fall so as to form a cross or ground. A **cross** or **ground** may be of such

low resistance as to form a short circuit or it may possess high resistance, thus forming what is called a *leak*. There are a number of different methods used for locating faults, and as those most suitable depend to a considerable extent on the kind of work for which the lines are used, most of the points relating to testing will be left until the different subjects with which they are connected are considered.

52. Continuity Tests.—In testing wires for continuity, the terminals of the magneto set should be connected to the terminals of the wire and the generator operated. A ringing of the bell will usually indicate that the circuit is continuous. This is a sure test on short lines, but should be used with caution on long lines and with cables, because it may be that the electrostatic capacity of the line wires themselves will be sufficient to allow enough current to flow through the ringer to operate it, even though the line, or lines, be open at some distant point.

53. Testing for Crosses or Grounds.—In testing a line for crosses or grounds, one terminal of the magneto should be connected to the line under test, both ends of which are insulated from the ground and from other conductors. The other terminal of the magneto set should be connected successively with the earth and with any other conductors between which and the wire under test a cross is suspected. A ringing of the bell will, under these conditions, indicate that a cross exists between the wire under test and the ground or the other wires, as the case may be, and the strength with which the bell rings, and also the pull of the generator in turning, will indicate, in some measure, the extent of this cross.

54. Here, however, as in the case of continuity tests, the ringing of the bell is not a sure indication that a cross exists if the line under test is a very long one. The insulation may be perfect and yet permit a sufficient current to pass to and from the line through the bell to cause it to ring, these currents, of course, being due to the static

capacity of the line itself. In testing very long lines or comparatively short lines of cable, the magneto set must be used with caution and intelligence on account of the capacity effects referred to. For short circuits in local testing, however, the results may be relied on as being accurate.

Magneto testing sets are commonly wound in such manner that the generator will ring its own bell through a resistance of about 25,000 ohms. They may, however, be arranged to ring only through 10,000 ohms, or where especially desired, through from 50,000 to 75,000 ohms. The first figure mentioned—25,000 ohms—is probably the one best adapted for all-round testing work.

CURRENT DETECTOR GALVANOMETER

55. In order to test for grounds, crosses, or open circuits on long lines or on cables, without the liability to error that is likely to arise in testing with a magneto set, a cheap form of galvanometer for detecting currents, called a **detector galvanometer**, may be used. In testing for grounds or crosses, the galvanometer should be connected in series with several cells of battery and one terminal of the circuit applied to the wire under test, it being carefully insulated at both ends from the earth and from other wires, while the other terminal of the galvanometer and batteries should be connected successively to the ground and to adjoining wires. A sudden deflection of the galvanometer needle will take place whenever the circuit is first closed, this being due to the rush of current into the wire that is necessary to charge it. If the insulation is good, the needle of the galvanometer will soon return to zero; but if a leak exists from a line to the ground or the other wire with which it is being tested, the galvanometer needle will remain permanently deflected.

In testing for continuity, the distant end of the line should be grounded or connected with another wire that is known to be good, and the galvanometer and battery applied, either between the wire under test and the ground or the wire

under test and the good wire. In this case, a permanent deflection of the galvanometer needle will denote that the wire is continuous, while if the needle returns to zero it is an indication of a broken wire.

56. Test for Insulation Resistance.—One thing that it is important to know about lines is the state of their insulation. In order to determine this, measurements of the insulation resistance between the line and ground must be made, and if this resistance is found to be dangerously low, the trouble should at once be looked up and remedied. One of the most convenient methods for measuring insulation resistance is by means of a good high-resistance voltmeter. The voltmeter is much easier to handle than a reflecting

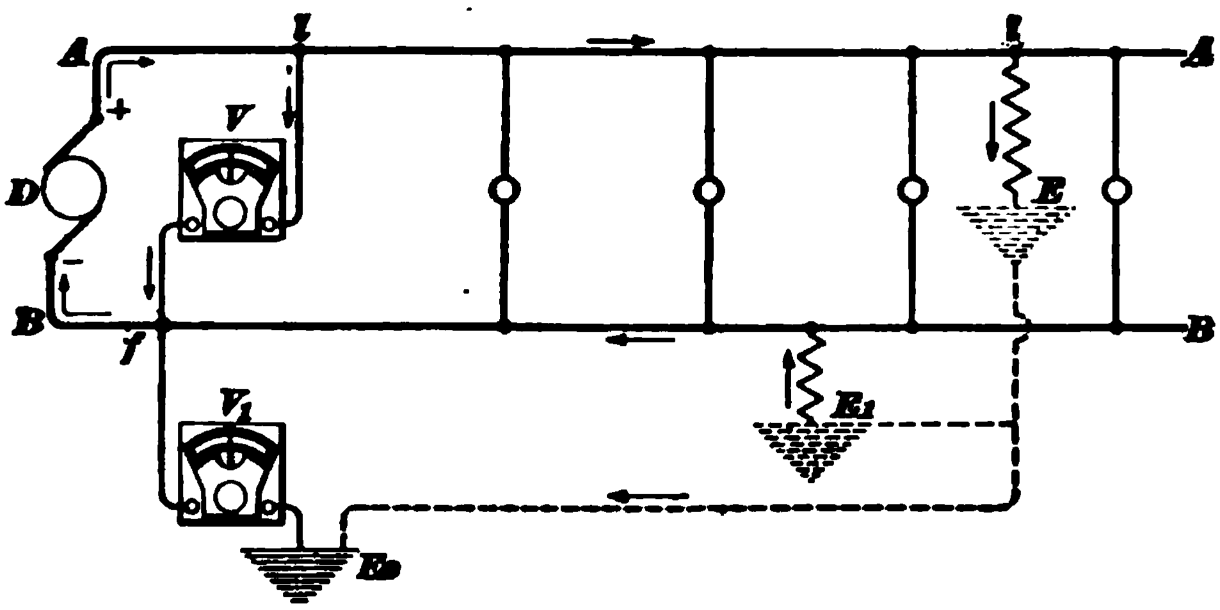


FIG. 51

galvanometer, and if the resistance of the voltmeter is known, insulation resistance measurements may be made with very little trouble. Suppose in Fig. 51 we wish to measure the insulation resistance of the line *A A*. The voltmeter is first connected across the lines at *V* in the usual manner and the voltage of the dynamo *D* obtained. Call this reading *V*. After taking the reading *V*, the voltmeter is connected between the line *B B* and the ground, as shown at V_1, and a reading V_1 obtained. In this case the current passes through the insulation from *l* to *E*, through the ground to E_2 and thence through V_1 to *f*. It is evident that if the insulation resistance of the line *A A* is very high, very little current will flow through the voltmeter,

and a small deflection will be the result. If the resistance r of the voltmeter is known, then the insulation resistance of the line will be

$$R = \frac{(V - V_1)\,r}{V_1} \qquad (3)$$

EXAMPLE.—The insulation resistance of an electric-light main was tested by means of a Weston voltmeter having a resistance of 18,000 ohms. When connected across the lines, the voltmeter gave a reading of 110 volts. When one line was connected to ground through the voltmeter, the reading was only 4 volts. What was the insulation resistance of the other line?

SOLUTION.—We have by formula **3**,

$$R = \frac{(110 - 4)\ 18{,}000}{4} = \frac{106 \times 18{,}000}{4} = 477{,}000 \text{ ohms. Ans.}$$

NOTE.—The insulation resistance of lines is usually expressed in megohms, 1 megohm being equal to 1,000,000 ohms. The resistance of the line in this case would therefore be .477 megohm.

TESTS FOR GROUNDS OR CROSSES

57. Varley Loop Test.—One of the most common methods for locating a ground or cross is by means of the **Varley loop test**. In Fig. 52, G is a sensitive galvanometer connected across the arms of a Wheatstone bridge in the ordinary manner; $A\,B$ and $A\,C$ are the ratio arms and $C\,D$

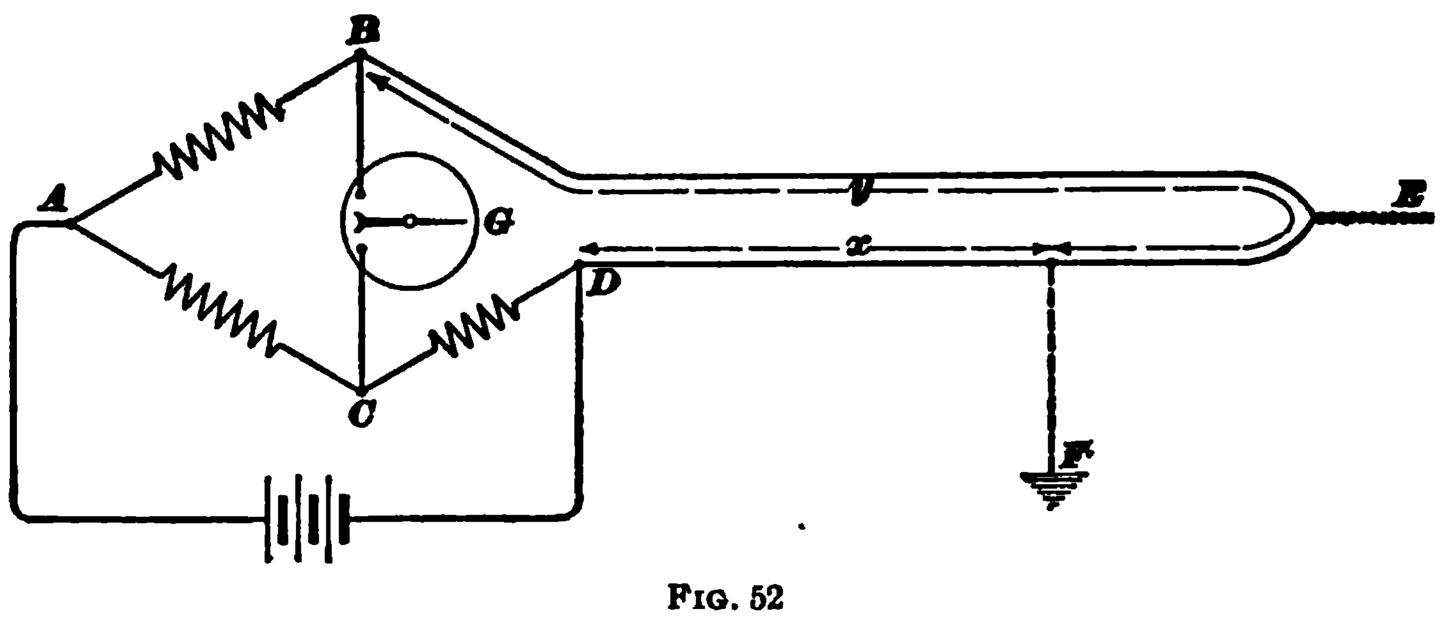


FIG. 52

the rheostat or balance arm of the bridge; $D\,E$ is the faulty line, $B\,E$ a good line, and F is the location of the fault. The two lines should be connected together at E and the ends of the loop $B\,E\,D$, so formed, connected across the terminals of the bridge as the unknown resistance. Call y the resistance

of the loop from B to F and x the resistance from D to F. With the battery connected between A and D, as in the ordinary method of using the Wheatstone bridge, balance the bridge. This will give, by working out the unknown resistance in the usual manner, a resistance R equal to the sum of the resistances of the two wires forming the loop; that is, $R = y + x$. Or, the resistance R of the whole loop may be calculated, if the length and size of the line wire are known.

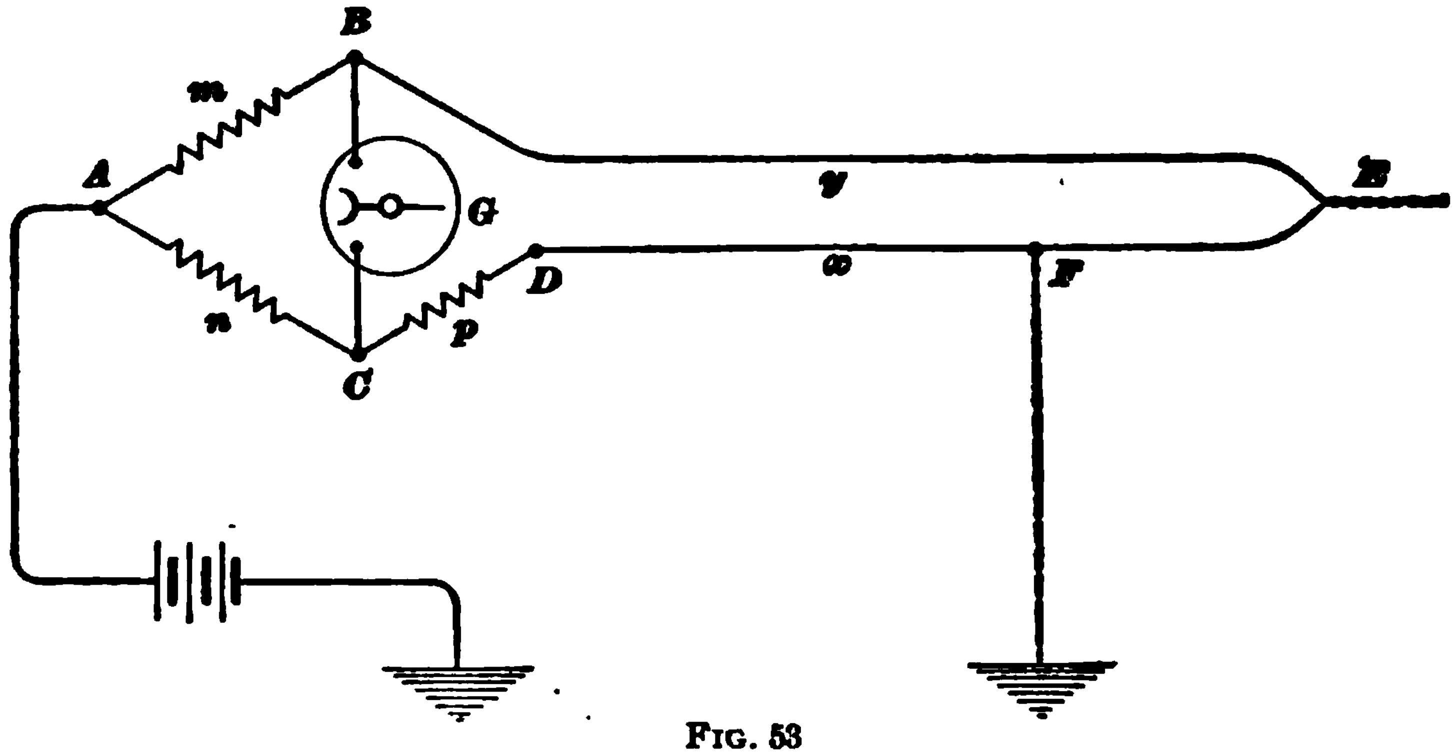


FIG. 53

Now disconnect the battery from D and connect it to the ground, as shown in Fig. 53. Then balance the bridge again, and the resistance x may be obtained by means of the following formula:

$$x = \frac{nR - mp}{m + n} \qquad (4)$$

in which m, n, and p are the values of the resistances in the arms $A\,B$, $A\,C$, and $C\,D$. After obtaining the resistance x from D to the fault F along the line $D\,E$ by means of formula 4, the distance (in feet or miles) from the testing end D to the fault F may be obtained by dividing this resistance x by the resistance of a unit length (a foot or a mile, as the case may be) of the line wire $D\,E$. The result obtained by this test is independent of the resistance at the fault between the line and the ground.

EXAMPLE.—A ground occurred on a conductor of a cable 10,000 feet long composed of three No. 10 wires. One good wire was used to

complete the loop. On testing with one end of the battery grounded as in Fig. 53, the bridge was balanced with the following resistances: $m = 10$ ohms, $n = 1{,}000$ ohms, $p = 1{,}642$ ohms. Where was the ground, the resistance per 1,000 feet of the conductor being .9972 ohm?

SOLUTION.—The length of the loop formed by joining the two wires of the cable at the distant end will be 20,000 ft.; hence, $R = 20 \times .9972 = 19.944$, and $x = \frac{1{,}000 \times 19.944 - 10 \times 1{,}642}{1{,}000 + 10} = 3.4891$. Hence, the distance of the fault from the testing station must be

$$\frac{3.4891}{.9972} \times 1{,}000 = 3{,}498.9 \text{ ft. Ans.}$$

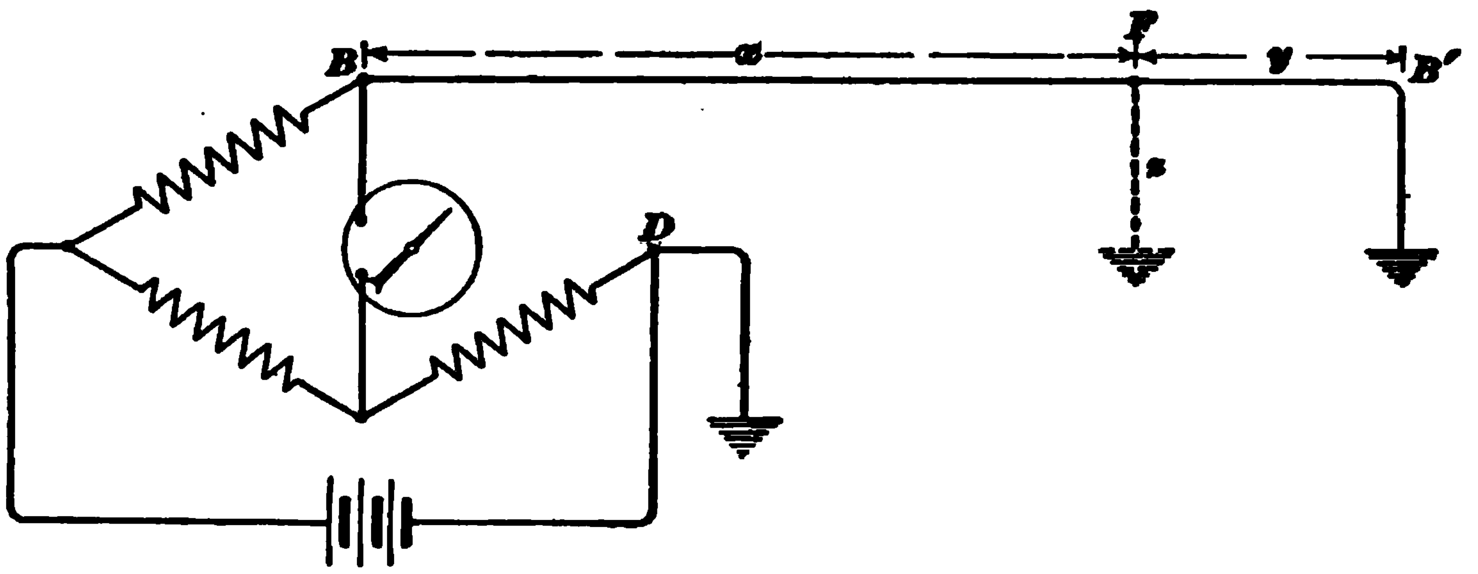


FIG. 54

58. Locating a Partial Ground Without an Available Good Wire.—The following method for locating a partial ground or leak is rather unreliable in practice, because the resistance of the partial ground may change

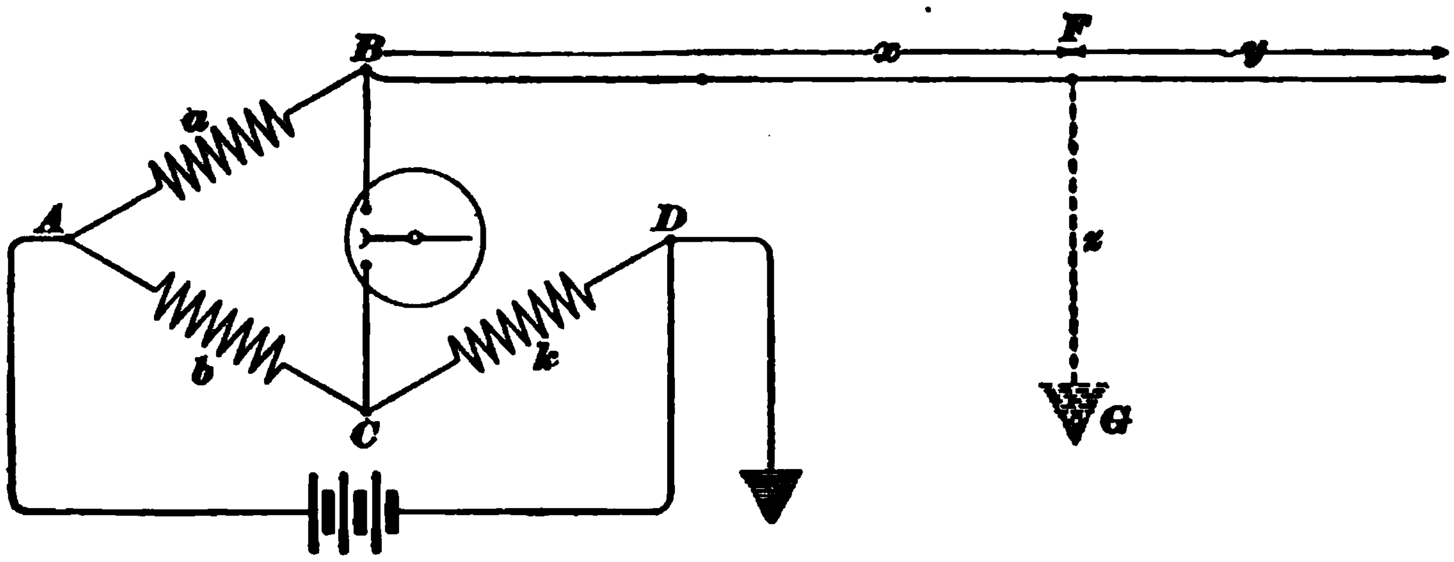


FIG. 55

between the two measurements, and so give a more or less incorrect result. However, it is about the only way where there is no available good wire and where the tests must be made from one end only. The normal resistance of the

line must be known from some previous measurement, unless it can be calculated from the length and size of the wire. Let this resistance be a; then measure the resistance of the line BB', with the distant end B' grounded as shown in Fig. 54, and call this c. Also measure the resistance with the distant end open, as in Fig. 55, and call this b ohms. Then the resistance x to the partial ground from the testing station is given by the following formula:

$$x = c - \sqrt{(b-c)(a-c)} \qquad (5)$$

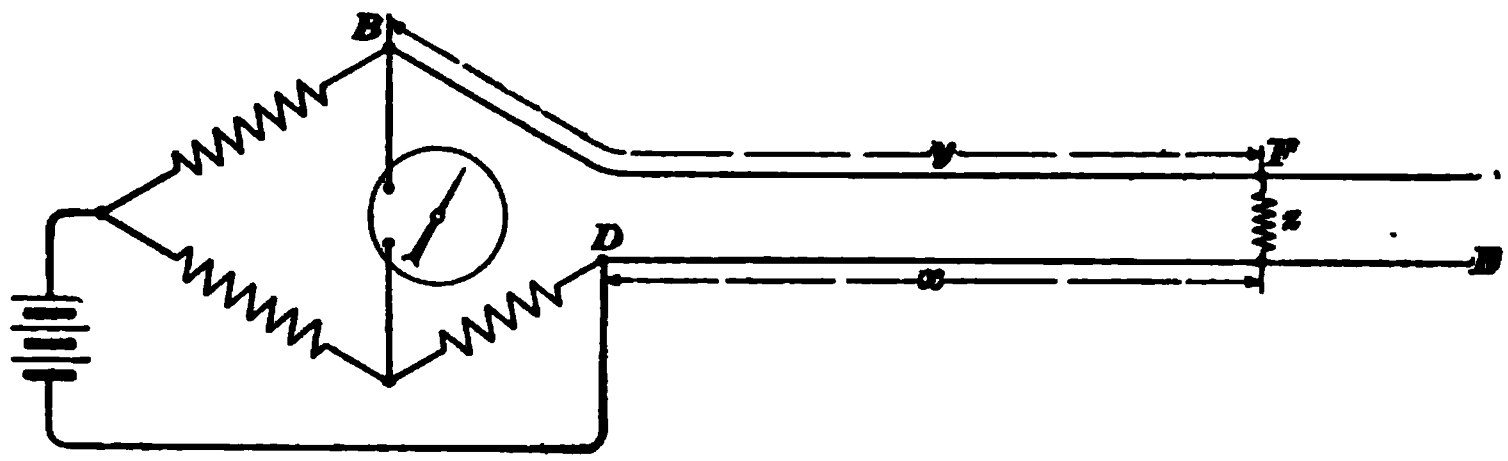


FIG. 56

By dividing x by the resistance per unit length of the wire, known from some previous measurements or by a calculation from its size, length, and a table of resistances for the kind of wire under consideration, the distance to the grounded point may be obtained.

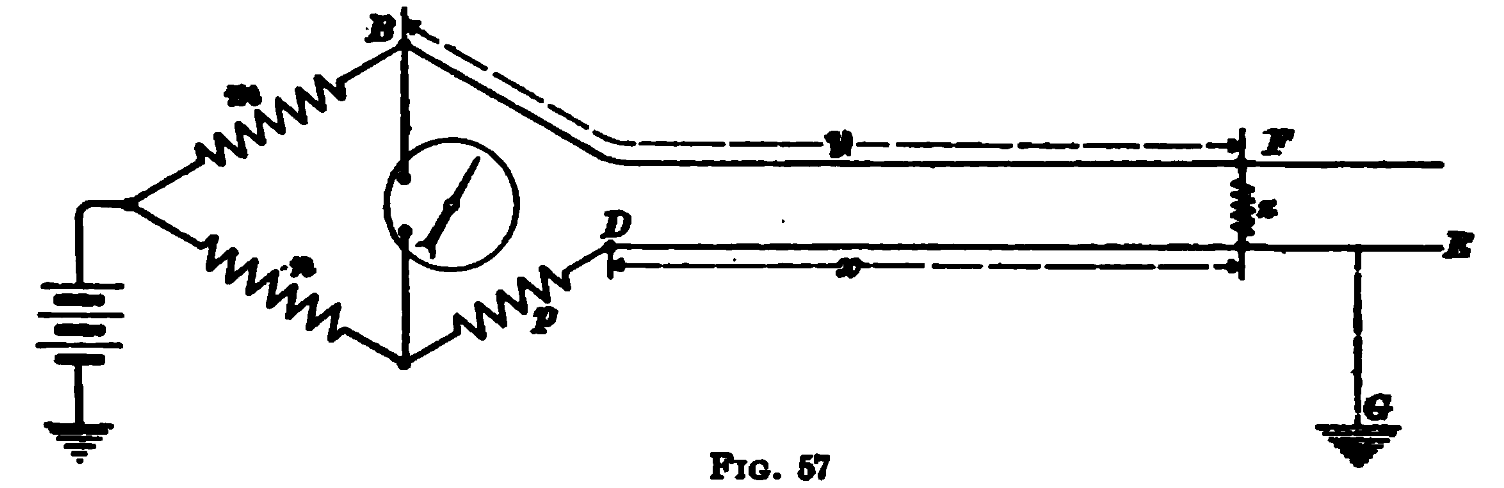


FIG. 57

59. To Locate a Cross by the Varley Loop Method. First insulate the distant ends of the two crossed wires. Then connect as shown in Fig. 56 and measure the resistance from D to B through the cross F. Let the resistance of the cross be z ohms and the resistance found by balancing the bridge be R ohms. Then,

$$R = x + y + z \qquad (1)$$

Now ground either wire, say DE, anywhere beyond the cross, and connect as shown in Fig. 57. When the bridge is again balanced, we have

$$\frac{m}{n} = \frac{y+z}{p+x} \qquad (2)$$

From equations (1) and (2), $x = \frac{nR - mp}{m+n}$.

This is the same as formula **4.** By dividing x by the resistance of the wire DE per unit length, we have the distance from D to the fault along the wire DE.

LOCATING GROUNDS AND CROSSES ON CONDUCTORS OF LOW RESISTANCE

60. The above tests, in which the location of a ground or cross is determined by means of resistance measurements, are capable of giving the location quite closely, provided the wire is fairly small, say less than No. 8 or 10 B. & S. When the wire is large, as it nearly always is in connection with power-transmission systems, bridge methods do not give the location close enough, because it is evident that a small resistance corresponds to a long length of conductor. The location of faults on these large conductors is of special importance in connection with underground distributing systems, and the bridge methods cannot usually be applied on account of the low resistance of the conductors. When a cross occurs between the conductors of an underground cable, it nearly always results in a ground also, because the consequent short circuit fuses the cable, thus making connection between the core and the sheath. One way of locating faults on underground cables is by the cut-and-try process already mentioned. A manhole is opened at a point near the middle of the line, and the cable is cut. Each half is then tested and the half on which the fault exists is then cut out at its middle point, and so on until the fault is located between two manholes. This method is slow and expensive, especially where high-tension cables are used, because the making of joints in such cables is a slow and costly operation.

61. Another method of locating faults is to run a heavy current through the cable so as to burn the insulation at the fault, and thus fill the duct and manhole with smoke. On opening the manholes the presence of the smoke indicates the location of the fault. This method, while more rapid and less expensive than the cut-and-try method, has the disadvantages that the burning of a cable, especially if near a manhole, is liable to injure other cables, and also that the burning is liable to ignite accumulated gases and thereby cause a subway explosion.

62. Fig. 58 shows, diagrammatically, a method recommended by Mr. Henry G. Stott,* which is particularly useful for locating faults on underground cables of large size. *A A*

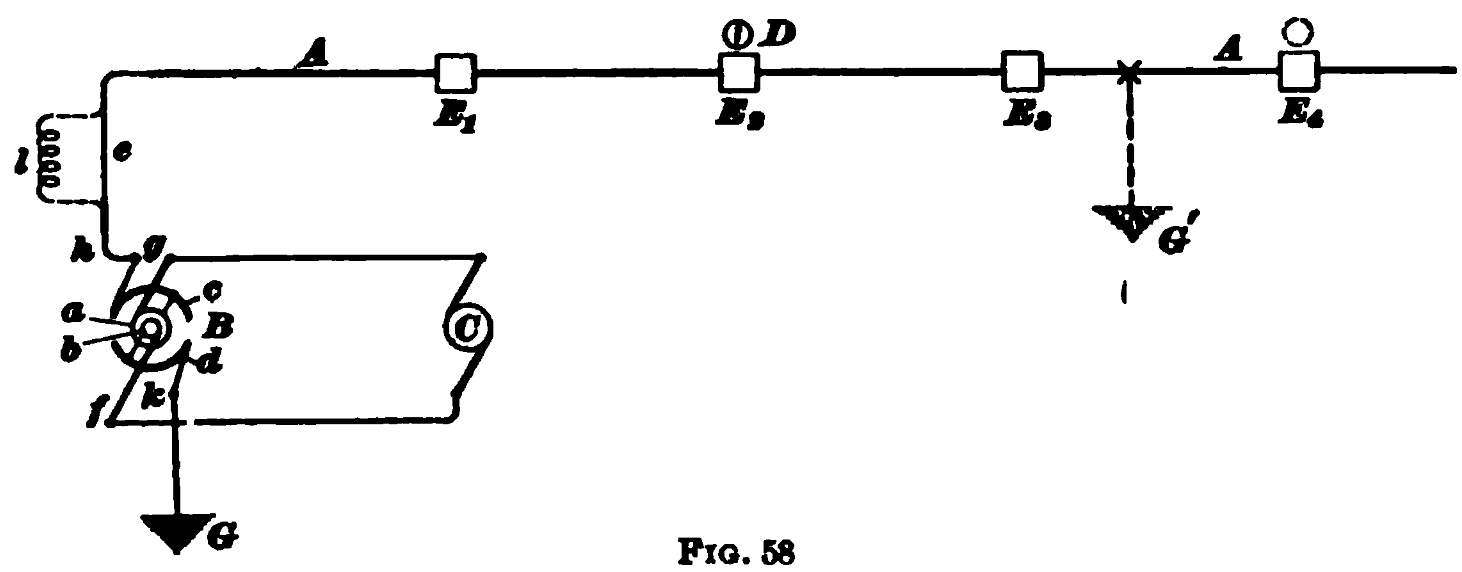


FIG. 58

is the cable running through a series of manholes E_1, E_2, etc. A ground has developed say at G', and this ground has to be located. C is a small direct-current dynamo; an arc light machine answers very well, because it maintains a fairly constant current, irrespective of the resistance of the circuit. B is a current reverser, which is revolved by means of a small motor. Brushes f, g, which press on the rings b, a, are connected to the terminals of C, and the contact arcs c, d are connected to the conductor and ground by means of brushes h, k. The rings a and b are connected to arcs c and d, so that as the contacts revolve, the current flowing through the cable to the fault G' and back to G is periodically reversed.

*Transactions American Institute of Electrical Engineers, Vol. XVIII.

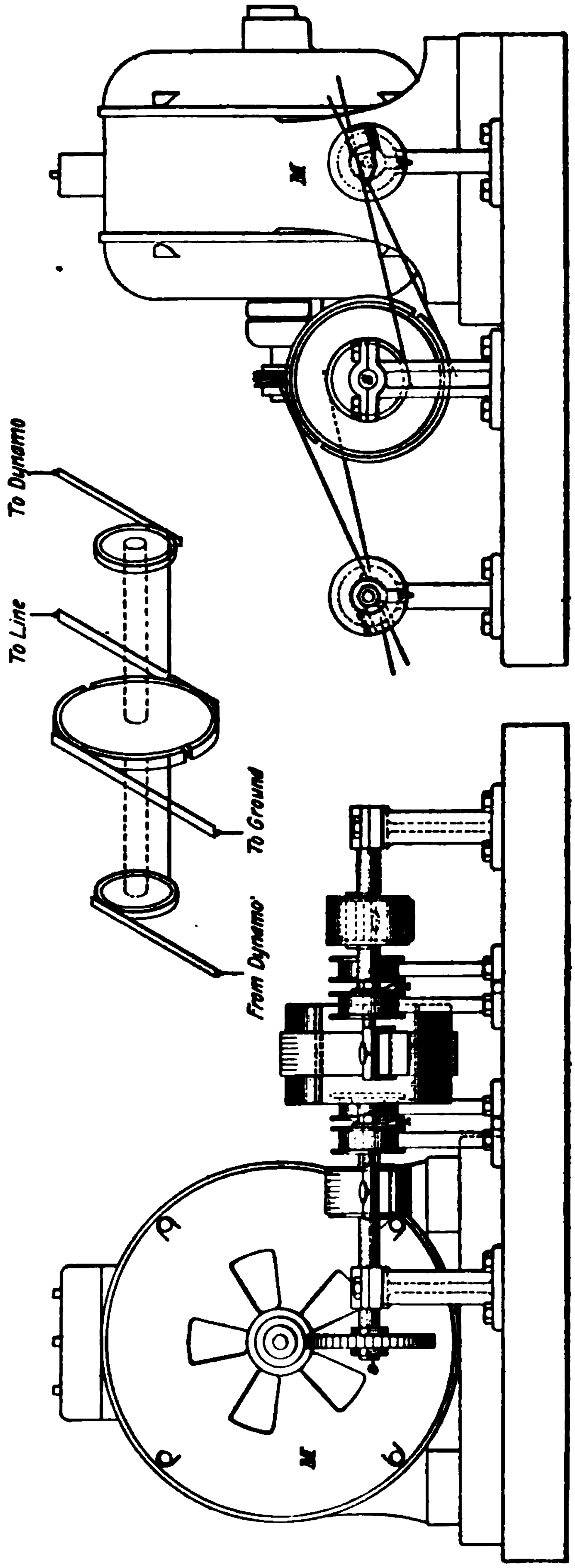


FIG. 59

The speed of the motor is such that the current is reversed once in about every 10 seconds. The fault is located by first opening a manhole about the middle of the line, say at E_2, and laying a compass D on the cable. The direct current, which need not be greater than 8 or 10 amperes, will cause the needle to swing first to one side and then to the other every 10 seconds. If the needle swings in this way at E_2, it shows that the fault is beyond E_2; hence, by this test, one-half of the cable is eliminated. The manhole is then closed and another test made at say E_4. At E_4 no reversals of the compass will be obtained, because the current does not flow in the cable beyond the fault. The fault is therefore located between E_2 and E_4; by opening a few intermediate manholes the

defective part is soon located between E_3 and E_4, and this section of cable can be removed and the fault remedied. It will be noticed that, with this method, the cable is not cut and the time required to make the test in each manhole is very short, so that the trouble is quickly located, and there are no joints to be made afterwards save those actually needed to replace the defective part of the cable.

In case the cable system carries alternating current and has no permanent ground attached to it, this device may be used for locating a fault even while the alternating current is on the system. The testing device is simply connected to the feeder network as shown, but in series between it and the network is placed a reactance coil, for example, the primary of a transformer, the circuit being opened at *e* and the coil connected in series as shown at *l*. This avoids damage to the dynamo *C* by preventing a rush of current from the alternating-current generators in case another ground should occur on the other side of the system while the test was being made, thus producing a short circuit. Before applying the test it is a good plan to break down the insulation resistance of the fault by applying a high potential, between the conductor and ground, for a few seconds.

Fig. 59 shows the style of reverser used in applying this test. An induction motor *M* drives the shaft *s* by means of a worm-gear. The two-part commutator revolves in oil so as to give a quick reversal of the current.

SWITCHBOARDS AND SWITCHBOARD APPLIANCES

SWITCHBOARD APPLIANCES

SWITCHES

1. Introduction.—The methods available for the transmission of electrical energy have been described in a general way, and it will now be necessary to examine more closely the various devices that are used for the control of the output of the generating plant. In order that a transmission system shall be under control, and also that the amount of the output, the condition of the lines, etc. shall be known, it is necessary to have various controlling and protective devices in the station. These are usually grouped together at one central point on the *switchboard*, and consist of switches, fuses, circuit-breakers, ammeters, voltmeters, ground detectors, lightning arresters, power factor indicators, wattmeters, and other auxiliary devices.

2. Probably the most important appliances on the switchboard are the **switches**, which are used for connecting or disconnecting circuits or dynamos from the rest of the system. Switches must be carefully selected with a view to the work that they have to perform. They must have ample carrying capacity and be capable of breaking the full-load current of the dynamo or circuit, without destructive burning or arcing. The style of switch used for any installation will depend on the voltage and current to be handled. For

convenience, we will consider switches as divided into two classes: *low-tension*, for handling pressures up to about 1,000 volts, and *high-tension*, for pressures above this amount.

LOW-TENSION SWITCHES

3. For pressures up to 1,000 volts, plain knife switches are generally used, though this style of switch with a broad separation of the blades and contacts has been used on pressures as high as 2,500 volts. For work of the latter class, however, it is preferable to use a switch of the quick-break variety, and even for pressures of 500 volts, quick-break knife switches are commonly used. Fig. 1 shows

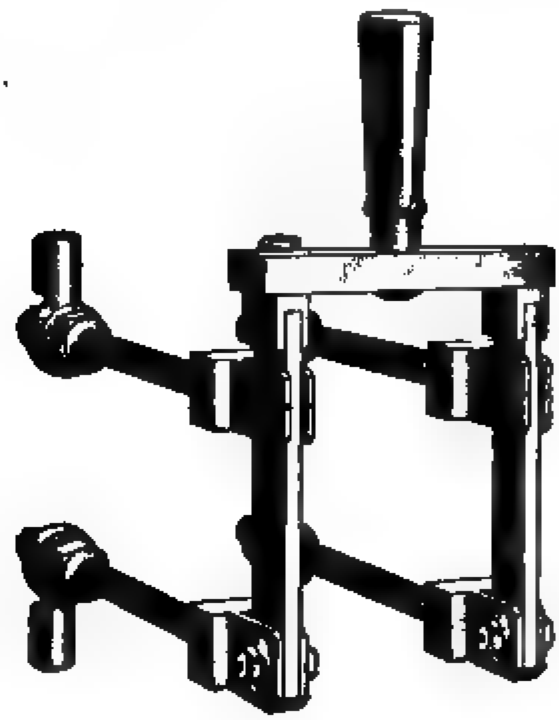


FIG. 1 FIG. 2

a typical two-pole knife switch designed for front connections and provided with fuses. Fig. 2 shows a similar switch without fuses and intended for mounting on a switchboard. When the switch is opened, connection is broken between the two clips at each side; thus opening both sides of the circuit. Knife switches should be substantially constructed and should have a contact surface at the clips of at least

1 square inch for every 50 to 100 amperes, the allowable current density being greater in small switches than in large ones. Bolted contacts will carry 200 amperes per square inch, and laminated contacts, such as are described later on in connection with circuit-breakers, will carry from 300 to

TABLE I

CURRENT DENSITIES FOR COPPER STUDS

Diameter of Stud Inches	Current Density Amperes per Square Inch	Diameter of Stud Inches	Current Density Amperes per Square Inch
$\frac{1}{2}$	1,200	$1\frac{1}{2}$	950
$\frac{3}{4}$	1,150	$1\frac{3}{4}$	850
1	1,100	2	800
$1\frac{1}{4}$	1,000	3	700

500 amperes per square inch. For copper studs the current densities, shown in Table I, should not be exceeded if the temperature rise is to be limited to about 20° C.

For the same temperature rise the current density must be smaller in large studs than in small ones, because in the large studs the heat is not so readily radiated.

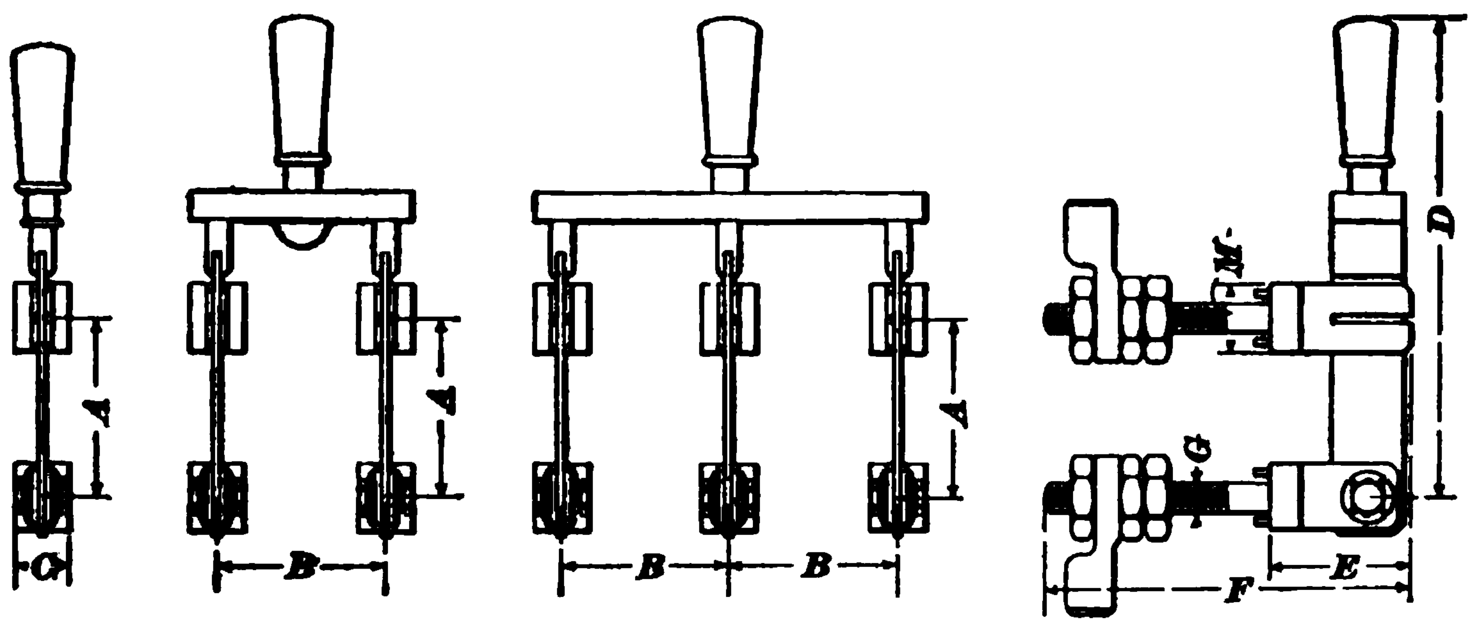


Fig. 3

4. The blades should be made of good conducting material, preferably of drawn copper, and the clips should be stiff enough to give a good, firm contact. For pure copper, the blades should have a cross-sectional area of about 1 square inch

per 1,000 amperes. Fig. 3, together with Table II, shows the dimensions, in inches, of General Electric knife switches.

Knife switches should always be mounted with the handles up; this is in accordance with a rule of the Fire Underwriters,

TABLE II

DIMENSIONS OF KNIFE SWITCHES

Capacity		Dimensions Common to All						Single-Pole		Double-Pole	Triple-Pole	Four-Pole
Amp.	Volts	*A*	*B*	*E*	*F*	*G*	*M*	*C*	*D*	*D*	*D*	*D*
25	125	1 3/8	1 5/8	1 11/16	6 3/16	3/8	5/8	5/8	4 7/16	4 5/8	4 5/8	4 3/4
50	125	1 5/8	1 7/8	1 11/16	6 3/16	3/8	5/8	5/8	4 11/16	4 7/8	4 7/8	5
100	125	2	2 1/4	2	6 1/2	3/8	3/4	3/4	5 3/4	6 1/2	6 1/2	6 5/8
25	250	2 1/8	2 3/8	1 11/16	6 3/16	3/8	5/8	5/8	5 3/16	5 3/8	5 3/8	5 9/16
50	250	2 5/8	2 7/8	1 11/16	6 3/16	3/8	5/8	5/8	5 11/16	5 7/8	5 7/8	6 1/16
100	250	2 3/4	3	2	6 1/2	3/8	3/4	3/4	6 1/2	7 1/4	7 1/4	7 7/16
200	125–250	3 1/4	3 3/8	2 7/16	6 15/16	1/2	1	7/8	7 3/4	8 1/8	8 1/8	8 1/4
300	125–250	3 5/8	3 1/2	3 1/4	7 3/4	5/8	1 3/8	1	9	9 1/2	9 1/2	9 5/8
500	125–250	4 3/4	4 1/8	4 1/4	8 3/4	3/4	2 1/4	1 3/8	11 1/4	11 7/8	11 7/8	13 1/8
800	125–250	5 1/2	5	5	9 1/2	1	2 3/4	2	12 3/4	13 3/8	13 3/8	14 1/8
1,200	125–250	5 1/2	5 3/4	4 1/2	10	1 1/4	2 1/2	1 3/4	12 5/8	13 1/4	13 1/4	
1,500	125–250	5 3/4	6	4 7/8	10 3/8	1 1/2	2 3/4	2 3/4	13	13 5/8	13 5/8	

which requires switches to be so placed that when open they will not tend to fall closed of their own accord.

5. Fig. 4 shows a style of quick-break switch that has proved very successful and is suitable for pressures as high as 2,000 to 2,500 volts if the current is not large. It has been very widely used on direct-current railway switchboards. The switch blade, of drawn copper, is made in halves

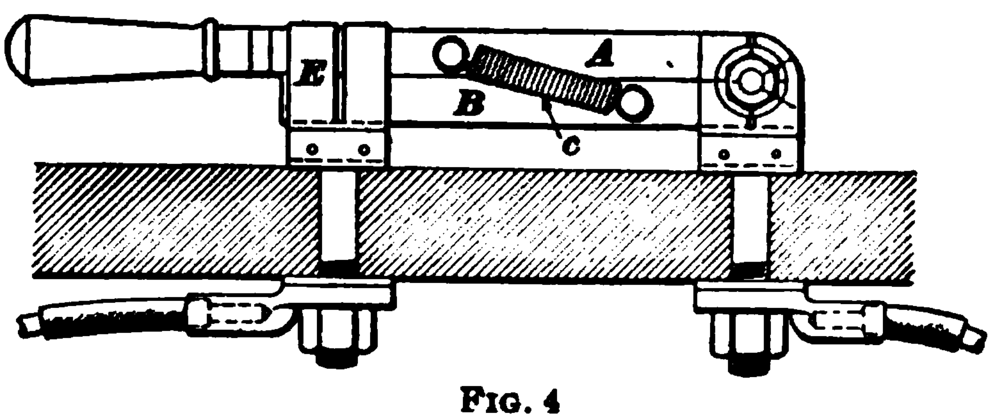


FIG. 4

A, *B*, which are connected by two springs *c*, one on each side of the blade. When the handle is pulled out, the half *A* leaves the clip *E* and thus stretches the springs. When the bottom blade flies out, it leaves clip *E* very quickly, thus drawing out the arc and breaking it almost instantaneously.

HIGH-TENSION SWITCHES

6. In long-distance transmission plants using alternating current, the pressures are very high, and in some cases also the volume of current is large. A switch to interrupt a heavy current at high pressure has to be carefully designed, and a great many types have been brought out. These may be divided into three general classes:* (1) Those in which the arc is interrupted in the open air; (2) those in which the arc is interrupted in a confined space; (3) those in which the arc is broken under oil.

These switches may be arranged for hand operation or they may be designed to operate automatically in case the current exceeds the allowable limit. If used in the latter way, they are generally called *circuit-breakers* to distinguish them from the non-automatic type. In many cases it is necessary to have high-tension switches arranged so that they may be operated from a distant point, because it is not practicable or even desirable to have high-pressure switches of large capacity mounted on or near the operating board.

SWITCHES BREAKING ARC IN OPEN AIR

7. In this type of switch the arc is simply pulled out until it is broken. Fig. 5 shows a modification of the switch shown in Fig. 4. This switch will handle a moderate current at pressures up to 5,000 or 6,000 volts, but where the volume of current is large, it is better to use a switch belonging to class (3).

The switch (Fig. 5) is constructed so as to give a long, quick break, and is mounted on grooved insulators *1*, *2*, *3*, *4*. This insulating material passes through the panel, so that in no place does the metal switch stud come in contact with the marble. This is a necessary precaution in cases where very high pressures are handled, because the marble cannot be depended on to give good enough insulation. Blade *A* has

*Classification given by E. W. Rice, Jr. Transactions American Institute Electrical Engineers, Vol. XVIII.

a hole in the end instead of a handle, and the switch is pulled open by means of a hook in the end of a handle about 3 feet long, thus allowing the attendant to stand back some distance and avoid the danger of being burned by the arc. To avoid arcing from one switch to the next, marble barriers *C* are mounted at right angles to the main part of the board.

For handling very high pressures, such as 20,000 volts and upwards, air-break switches have been used to quite a large extent. In these switches, the movable contact is generally mounted on one end of a long arm, so that when the arm is thrown out, a break of several feet is made in the circuit.

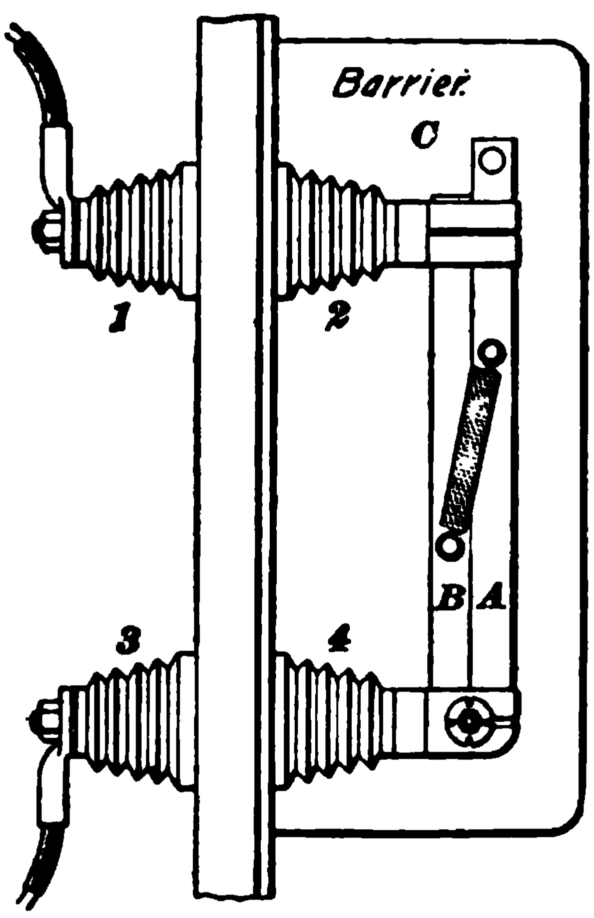


FIG. 5

8. Stanley Plug Switch. Fig. 6 shows a type of air-break switch made by the Stanley Electric Manufacturing Company, and used on pressures as high as 30,000 volts, at which pressure it is capable of handling a current of 25 amperes. A long wooden handle *a* is provided with a terminal *b* on its upper end, and this terminal is connected to a plug *c* by means of a flexible cable *d*. When plug *c* is inserted, it makes contact with a terminal sunk well below the surface of the marble, where it cannot be touched accidentally. Also, it is locked in position, so that the circuit cannot be accidentally opened at this point. The terminals *e* and *f* are mounted on ribbed porcelain insulators, and are made in the form of tapered points, as shown, so that the tip *b* may be slid over them. Hard-rubber guides arranged below the porcelain insulators engage with the projection cast on *b*, so that the handle *a* must be pulled straight down for a short distance when the switch is being opened, thus preventing terminals *e*, *f* from being bent.

When the handle has been pushed up into place, it is held by clamps *g*, *h*. The switch shown in Fig. 6 is of the double-throw type, i. e., terminal *c* can be connected to either *e* or *f*; a marble barrier *k* is placed between the terminals to prevent arcing across. When the switch is opened, the handle is pulled down until the contact is separated from the taper plug, and it is then swung back over the operator's shoulder and moved away from the board until the arc is ruptured. The tapered terminals and the terminal on the handle are provided with zinc tips, as it has been found that the arcing does not roughen up the zinc to the same extent as copper. One advantage of this type of switch is that the live terminals are at the top of the board out of reach of the operator. By unlocking plug *c*, the handle with its cable may be removed entirely if it is desired to clear the board.

FIG. 6

SWITCHES BREAKING THE ARC IN A CONFINED SPACE

9. Westinghouse Plunger Switch.—Fig. 7 shows a Westinghouse switch where the arc is broken in a confined space. The terminals are mounted at each end of a porcelain cylinder. A copper rod or plunger passing through these contacts or bushings completes the circuit, and when the plunger is withdrawn, the arc is formed in the confined space between the bushings. A small outlet is provided in the side of the tube, and when the arc is formed, the blast caused by the sudden expansion of the air in the confined space, together with the cooling action of the porcelain walls,

extinguishes the arc. If the pressure to be handled is very high, a number of these cylinders are connected in series, thus producing a long break. The cylinders *1*, *2*, *3*, etc. and plungers *1'*, *2'*, *3'* are mounted on the back of the board and are operated by a lever on the front. In the figure the switch is shown thrown out, but when the plunger is in, bushings *a* and *b*, *c* and *d* are connected together, and the path of the current is *a–b–c–d–c* to line. When the plunger is withdrawn, the arc is broken between *a* and *b*, *c* and *d*.

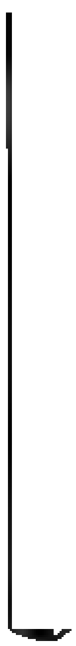


FIG. 7

10. Stanley Slide Switch and Circuit-Breaker.

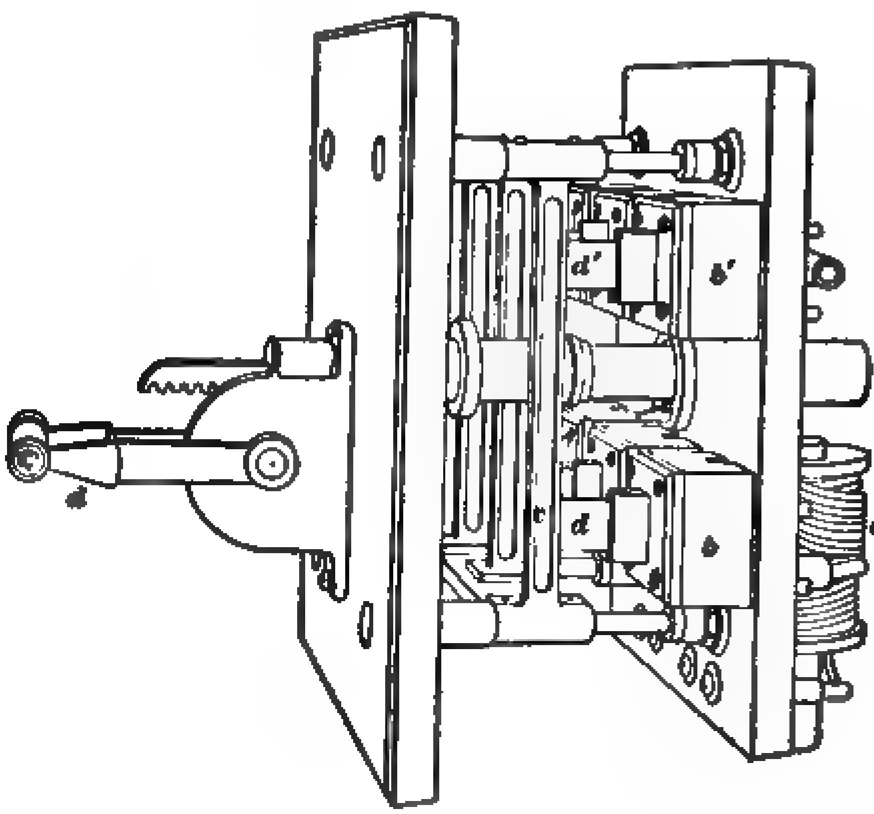
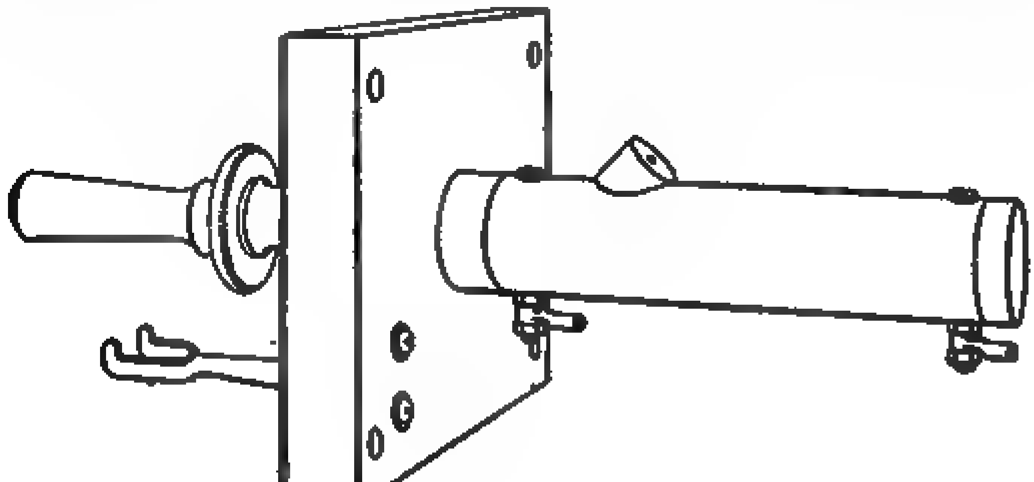


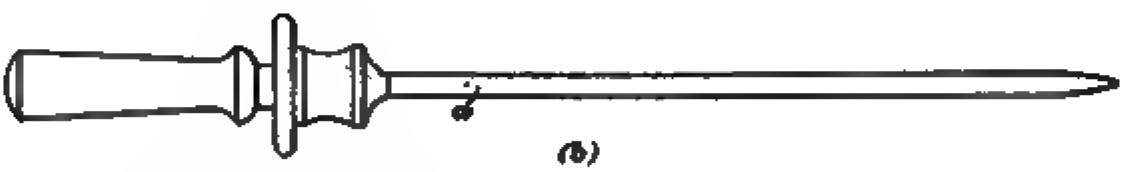
FIG. 8

Fig. 8 shows a Stanley slide switch provided with an

automatic attachment that will open the switch whenever the current exceeds the amount for which the circuit-breaking device is adjusted. The attachment consists of a solenoid *a* through which the main current flows. When the current exceeds the allowable amount, the solenoid releases a catch and a spring throws the switch out. If it is not desired to use the switch as a circuit-breaker, the automatic device can be cut out. The switch terminals are mounted in the insu-



(a)



(b)

FIG. 9

lating blocks *b*, *b'*, of which there are two for each pole; in this case there are six terminals, the switch being three-pole. For each pole there is a cross-piece *c* provided with blades *d*, *d'* that make contact with the terminals when they are forced in by swinging the handle *d* up. The motion of *d* is transmitted to the cross-pieces *c* by means of a rack and pinion, and when the switch is opened the blades are withdrawn from the

clips; as soon as they leave the insulating pieces, a shutter arrangement closes the opening, thus preventing the arc from following the blades. Switches of this type are made in a number of different sizes and are capable of handling as high as 60 amperes at 3,300 volts. The present practice, however, is to use oil switches for most high-pressure work.

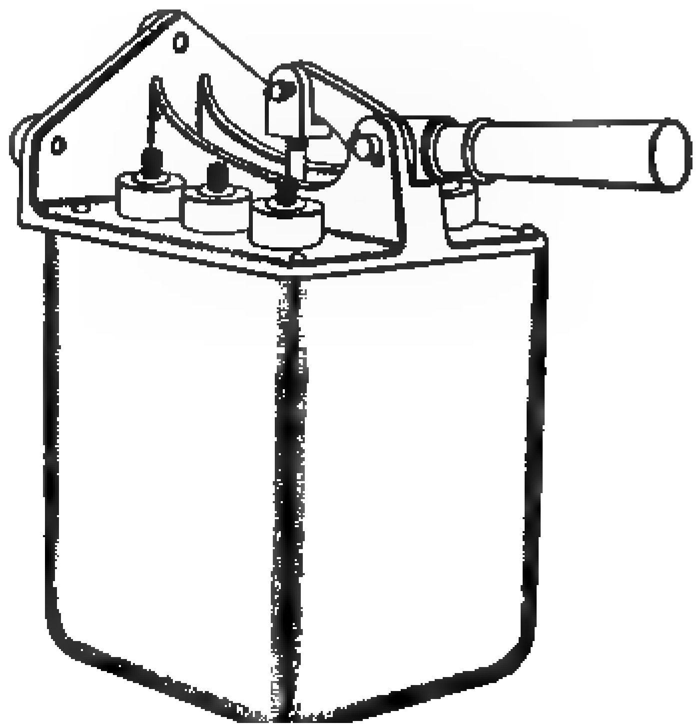
11. Stanley Stab Switch.—Fig. 9 shows a simple form of high-tension switch that is capable of handling a current of 10 amperes at pressures as high as 7,000 volts. When the rod *a* is inserted, contact is made between the bushings *b*, *c* mounted in a thick fiber insulating tube. When *a* is withdrawn, the marble ball *d* drops from the cavity *e* in which it is held by the rod, and takes the position shown, thus effectually smothering the arc. The vent *f* provides an exit for the heated air. Switches of this type are particularly adapted for high-pressure, series-arc lighting circuits or series-incandescent lighting circuits.

SWITCHES BREAKING ARC UNDER OIL

12. It has been found that circuits carrying large currents at high pressure can be successfully broken by separating the terminals under oil, and oil-break switches have come much into use within the last few years. Circuits in which there is more or less inductance, producing a lagging current, require more effective switching devices than those in which there is no inductance, because the induced E. M. F. always tends to prolong the arcing when the switch is opened. Oil switches have proved very efficient on circuits of this kind. As soon as the switch terminals are separated under oil, the oil fills the gap and arcing is effectually suppressed with a comparatively short separation of the terminals. It was at first thought that the very sudden break caused by a switch of this kind might give rise to severe strains on the insulation of the system, but this has not proved to be the case, and oil switches are now very largely used, both in central stations and also in connection with motors or other apparatus using alternating current. There are many different

reliable makes of oil switches, but for purposes of illustration we will select a few examples of the General Electric type.

13. General Electric Oil Switches.—Fig. 10 (*a*) and (*b*) shows a switch designed for mounting on the front of the switchboard or for individual use with motors or other apparatus. The same style of switch is made for mounting behind the switchboard with the operating handle on the front of the board; (*b*) shows the switch with the oil tank removed. In this case a triple-pole, single-throw switch is illustrated, though the same type is made in single-pole, double-pole, and four-pole, and for either single-throw or double-throw. The terminals *a*, *a*, *a* are mounted in the porcelain insulators *b*, *b*, *b*. The contacts *c* are hinged as shown, and are connected together by a wooden cross-piece *e* connected to the operating handle. The other contacts *d* make a firm wiping contact with *c* when the switch is closed. The wires leading to and from the switch are attached to the terminals *a*, *a*, *a*



(*b*)

FIG. 10

so that they do not pass through the oil tank, and there is, therefore, no chance for oil leakage if the tank is not filled too full. This type of switch is recommended for use with all inductive appliances, such as induction motors, that operate at 250 volts or higher. It is not intended for circuits operating at pressures higher than 3,500 volts or in cases where the load exceeds 850 to 1,200 kilowatts, three-phase, under emergency conditions; i. e., under a short circuit or very heavy overload.

14. Fig. 11 (*a*), (*b*), and (*c*) shows another General Electric switch of larger capacity. This is made single-, double-, triple-, and four-pole, and for single-throw only. The load that it can rupture under emergency conditions must not exceed 3,500 kilowatts, and the pressure 6,600 volts. For potentials exceeding 5,000 volts, the switch is not mounted on the back of the switchboard, as shown in Fig. 11, but is placed in a fireproof compartment entirely detached from the board. The operating handle on the board is connected with the switch by means of a series of levers. By this arrangement, the danger of fire at the switchboard is minimized and the operating devices can be entirely separated from the high-tension parts of the switch. Fig. 12 shows the general arrangement referred to, though, of course, the actual arrangement of the levers would depend on the relative location of the operating board and switch. These switches are arranged for simple hand control, or they can be provided with an attachment that will open them automatically in case the load becomes excessive, thus combining the feature of a switch with that of an automatic circuit-breaker. Fig. 11 (*a*) shows the operating handle provided with the automatic attachment; (*b*) shows the arrangement for hand control; (*c*) shows the construction of the switch proper with the oil tank removed. The terminals are held in the porcelain insulators *b*, *b*, *b*, which are ribbed in order to interpose a large leakage surface between the terminals and the framework of the switch. When the operating handle is pushed in, the metal cross-pieces *c*, *c*, *c* are raised by the

FIG. 11

system of levers and brought into contact with the fingers *d*, *d*, *d*, thus completing the circuit. Each cross-piece *c* is attached to a wooden rod *e*, and these rods are attached to a common crosshead that is moved up or down by the levers controlled by the operating handle. When the oil tank is in place, the contacts *c* and *d* are completely submerged in oil.

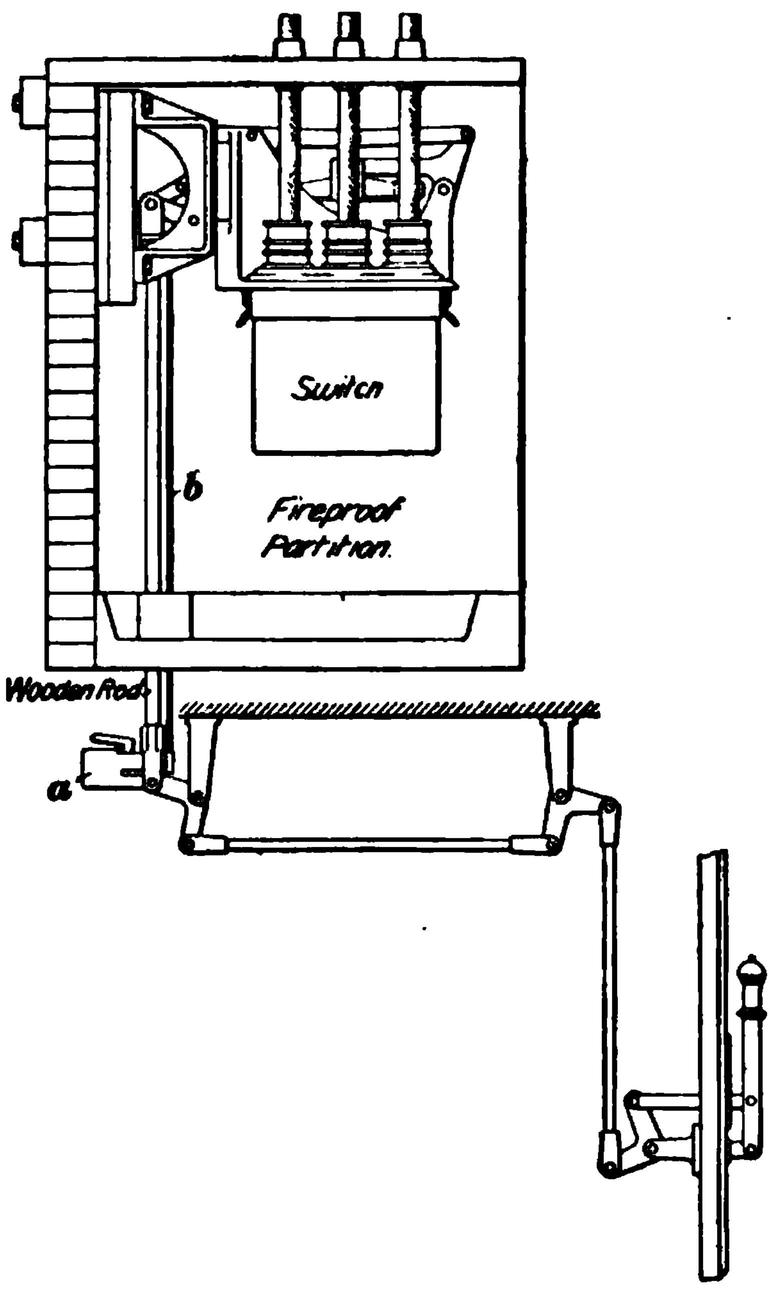


Fig. 12

15. The automatic tripping mechanism used when the switch is mounted on the board is shown in (*a*). It consists of two solenoids *f*, *f*, which, when the current becomes excessive, draw up their cores, which strike the lever *g*, *g*. This releases the link *h* that connects the operating handle with the switch and allows the switch terminals to separate. The link *h* slides out through the operating handle, but the handle itself remains in. The projecting link, therefore, acts as an indicator and shows that the switch has opened automatically. When the switch is opened by hand, the button *k* on top of the operating handle must first be pressed down.

16. Fig. 13 shows the connections for the tripping coils when the tripping mechanism is placed at the switch as in Fig. 11. The windings of the coils, Fig. 13, are connected to the secondaries of two current transformers, the primaries of which are in series with the mains, as shown. If the current in the mains becomes excessive, the current in the secondaries and tripping coils increases in like proportion, and if the current exceeds the value for which the armatures

of the coils are adjusted, the switch is opened by the operation of either one or both of the coils.

When the switch is not mounted on the board, the tripping coil is operated through an overload relay or auxiliary pair of magnets, as shown in Fig. 14. In Fig. 12, the tripping coil is located at *a*, and consists of a single coil, the armature of which moves the light wooden rod *b* and allows the switch to open promptly whenever there is an overload. In Fig. 14, *a* is the tripping coil and *b*, *c* the coils of the overload relay situated on the switchboard or at any other convenient point. Under normal conditions the contacts *d*, *e* of

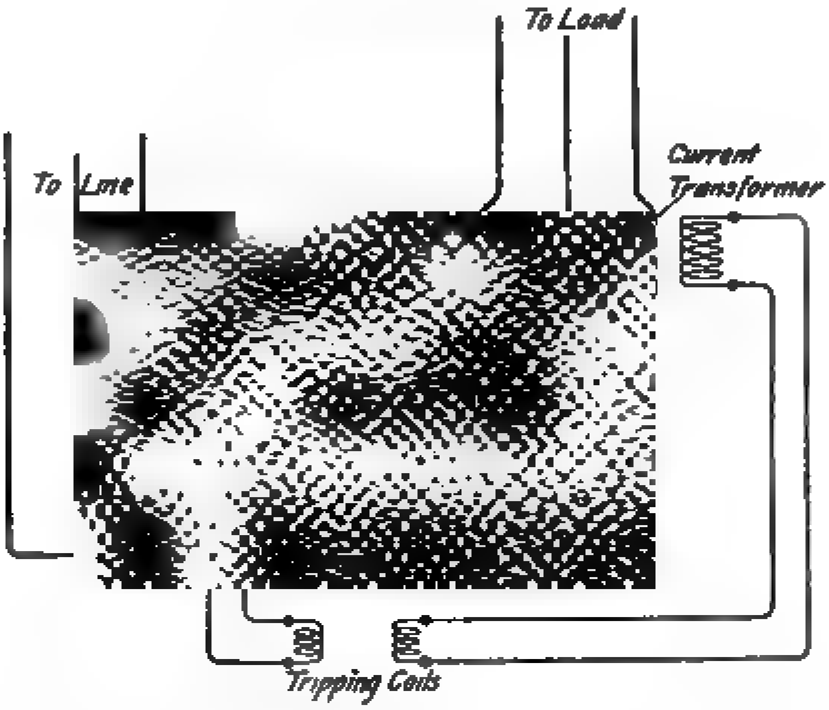


Fig. 13

the relay short-circuit the tripping coil, but in case the current becomes excessive, either one or both of the coils draw up their cores and raise contacts *d*, *e*, thus making the current from the series-transformers take the path through the tripping coil *a* and opening the switch.

17. Oil Switch of Large Capacity.—Fig. 15 shows two views of a General Electric oil switch of large capacity for use in central stations handling large alternating currents at high pressure. The switch is arranged for control from a distant point, the movements being effected by means of an

electric motor. These switches have also been built for operation by compressed air, and the Westinghouse Company make a somewhat similar switch operated by solenoids. The casing of the switch shown in Fig. 15 is made of brick, and is provided with a removable iron door. The casing is divided into three compartments, one for each phase, and since they are separated by brick partitions, a burnout, if it should occur, cannot spread to other parts. These switches are designed with a view to using the smallest possible amount of oil, because where there are a large number placed in a plant, the presence of a large quantity of oil in the switches would introduce a serious

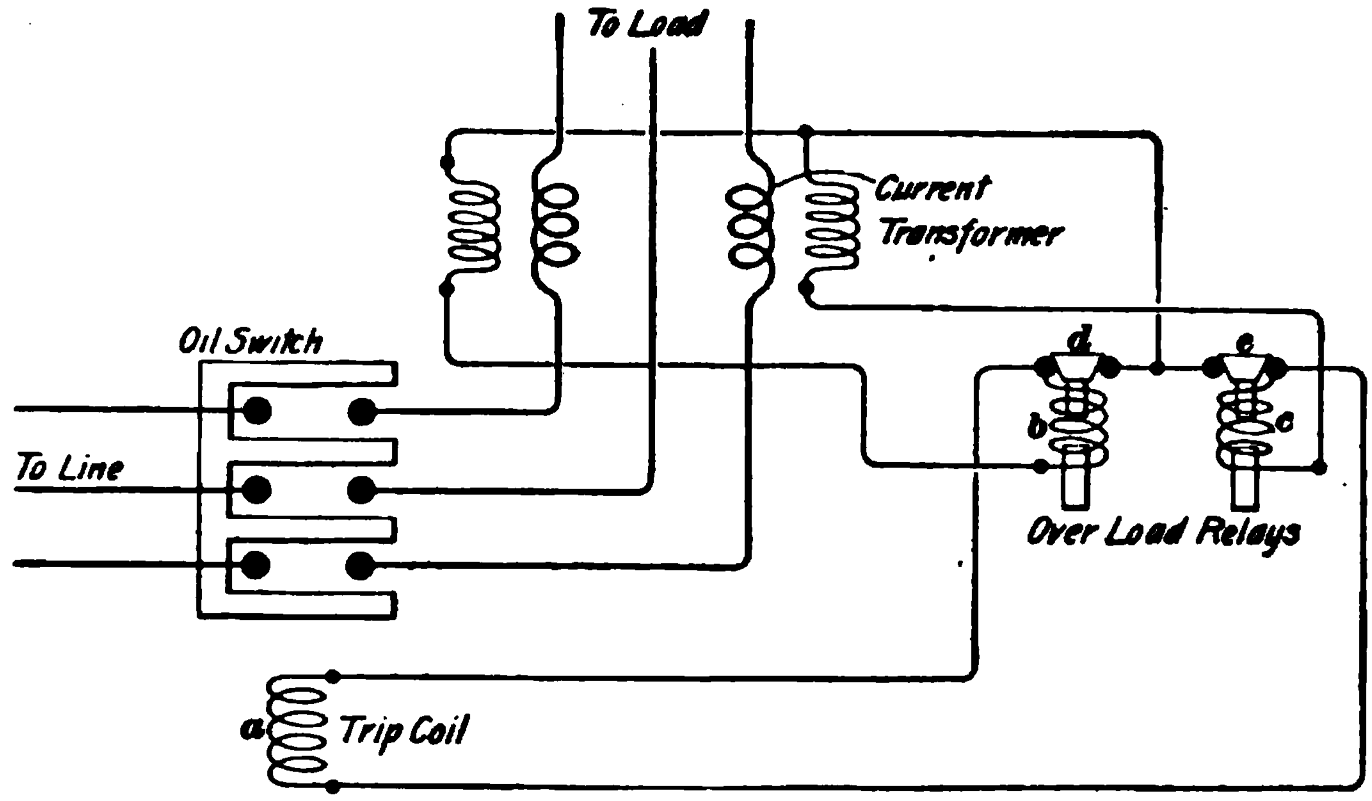
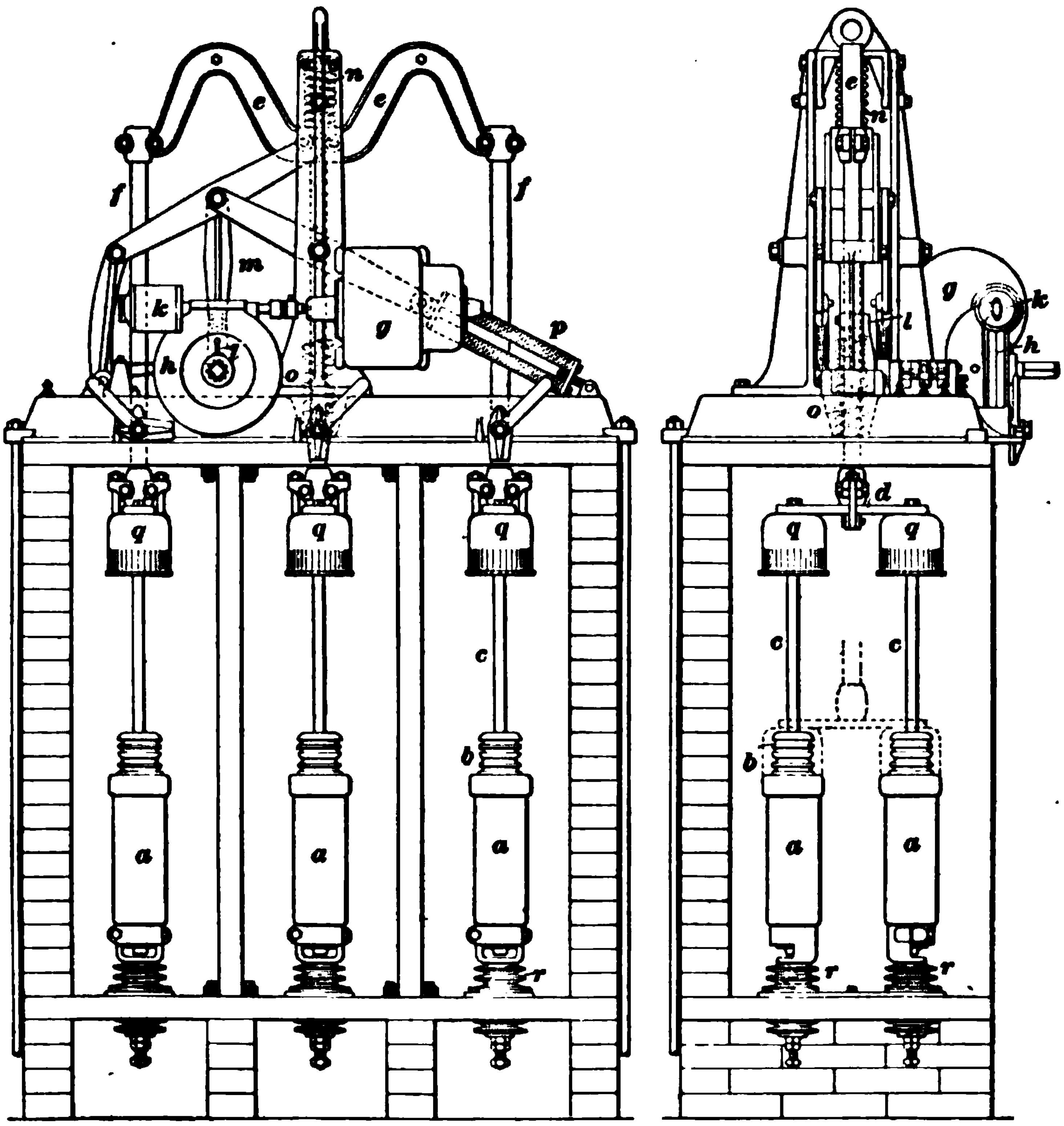


FIG. 14

fire risk. In each compartment is a pair of brass cylinders *a*, *a* with a contact sleeve at the bottom of each. These cans or cylinders are lined with insulating material, are filled with oil, and are provided with porcelain insulating sleeves *b* at the top through which slide copper rods *c*. The two rods are connected together by the cross-piece *d*, so that when the rods are pushed down into the contact sleeves in the bottom of the cylinders, the two cylinders are electrically connected, the current passing from one cylinder to the other by way of rods *c*, *c* and cross-piece *d*. The cross-pieces *d* are attached to a crosshead *e* by means of wooden rods *f*, and the motion of the crosshead is controlled by means of the motor *g*.

The motor is thrown into gear with a worm that operates a worm-wheel in the casing *h*, whenever the solenoid *k* is excited from the switchboard. On the worm-gear shaft is a crank *l* which together with a link *m* forms a togglejoint. When the switch is out, as shown in the figure, spring *n* is compressed and the switch tends to close, but is prevented



(a) (b)

Fig. 15

from doing so because the toggle *l m* is on center. As soon as the motor is started from the switchboard, the crank *l* is moved off center and the crosshead *e* is at once forced down. The crank *l* is driven from the worm-gear by means of a ratchet, so that as soon as the toggle is moved off center,

the crank is carried around through nearly a half revolution independently of the movement of the motor. As soon as the crank stops, the ratchet at once takes hold and the crank is turned through the remainder of the half revolution until the toggle is again on center. The switch is now completely closed, and the motor is stopped automatically by means of a rotating switch moved by the worm-gear shaft. When the switch is closed, spring o is compressed and springs p are stretched. The switch is opened by starting the motor from the switchboard, as before, thus throwing the toggle off center again and allowing the springs to throw up the cross-head. In the opening operation, the springs p assist spring o, so that the opening is quicker than the closing, the time

FIG. 16

required being about 1 second. For switches that have to handle large currents, the rods c, c are provided with auxiliary bell-shaped contacts q, q, which, when moved down to the dotted position, make contact with the upper part of the cylinders, thus relieving the rods of the current. When the switch moves up, these contacts leave the cylinder before the contact is broken inside the cylinder, so that no arcing takes place at the auxiliary contacts. The cylinders are mounted on ribbed porcelain insulators r, r, and are arranged so that they can be easily removed from these supports. The switch shown in Fig. 15 has a range of movement of 17 inches and is capable of handling 300 to 800 amperes at 12,000 volts.

18. Stanley Oil Switches.—Figs. 16 and 17 show two types of **Stanley oil switch.** The switch shown in Fig. 16 is of the double-pole, double-throw type with the oil tanks mounted side by side. Fig. 17 shows a three-pole, single-throw switch with the tanks mounted one behind the other, so that the switch can be mounted on a narrow panel. The oil tanks *a*, *b*, *c* are of cast iron with an enamel lining, and are mounted under the marble slab *d* to which the fixed switch terminals *e* are attached. The slab *d* is supported by iron castings, and the switch arms *f* are operated by means of the levers, as indicated, thus throwing the blades *g* into or out of contact with the fixed clips. The terminals *i* are protected by wooden boxes, and the operating handle *k* is thoroughly

FIG. 17

insulated from the working parts of the switch by the wooden arm *l*. The tanks are arranged so that they can be easily refilled. There are two breaks in each leg of the circuit; in Fig. 17, for example, there are two fixed clips *e* in each tank, and the two corresponding blades *g* are connected together.

BUS-BARS

19. Bus-bars should have a cross-section of at least 1 square inch per 1,000 amperes and should be arranged so that the heat generated in them can be readily radiated. They should be substantially mounted and carefully insulated, particularly in cases where a high pressure is used. The bars are usually of flat rectangular cross-section; and if

large current-carrying capacity is required, a number of thin bars are built up with air spaces between to allow ventilation. Thus, a bar made up of four bars $\frac{1}{4}$ inch thick with a $\frac{1}{4}$-inch air space between each bar would be much better than a solid bar 1 inch thick. Heavy solid bars should not on any account be used with alternating current. Where bars are made up of a number of thin bars with air spaces between, joints are readily made by interleaving the bars and bolting through, thus giving a large contact area. Round bars and copper tubes are occasionally used for bus-bars but they are not as desirable as flat bars except,

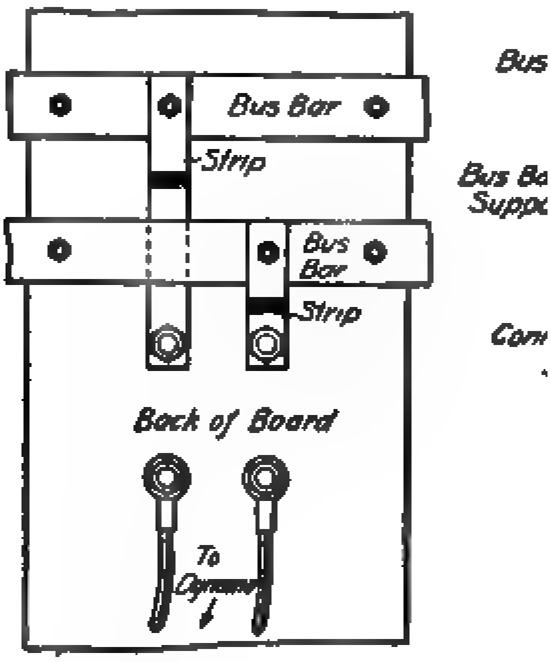


FIG. 18

perhaps, for high-tension boards, where the current to be handled is small and where it is desirable to have the bars covered with insulating material.

Fig. 18 shows a simple method of mounting bus-bars for small low-pressure switchboards. Fig. 19 shows a method that has been largely used on 500-volt railway switchboards.

20. Carrying Capacity of Bus-Bars.—Bus-bars should be of liberal cross-section, otherwise the loss in them may be considerable. For aluminum bars, a density of from 500 to 600 amperes per square inch is allowable. Cast copper is much inferior to rolled or drawn copper as a conductor,

and the density in cast bars, studs, or fittings should not exceed 500 amperes per square inch. Brass can carry from 100 to 350 amperes per square inch, depending on the amount of copper in its make-up.

21. Mounting for High-Tension Bus-Bars.—When bus-bars have to handle a large current at high pressure, it is very important that they be mounted so that there is practically no possibility of a short circuit taking place between them. A short circuit on such bars might cause a great deal of damage, particularly if a number of machines happened to be feeding into the bars at the time. It has

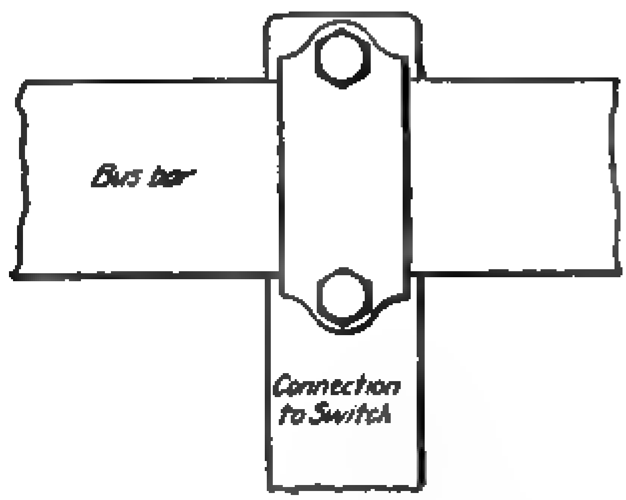


FIG. 19

become customary, therefore, in large stations supplying current at high pressure, to mount the bars on fireproof supports and separate them by fireproof partitions so that each bar shall be in a compartment by itself. Fig. 20 shows the method of mounting 6,600-volt bus-bars in a large station in New York city. The bus-bar *a* is made up of four rolled copper bars 3 inches wide by $\frac{1}{8}$ inch thick, and is bolted to a stud *b* that is covered with an insulating tube *c*. The bar, with its connecting stud, is supported on a firebrick slab *d*, this slab being built into the brickwork *e f*. Thorough insulation is provided by the grooved porcelain insulators *g*, *g*.

and connections are made to the bar by means of the cable terminals *h*, *h* and plate *k*. Firebrick or soapstone slabs

FIG. 20

projecting at right angles to the wall *e f* are used as barriers between adjacent bars.

VOLTMETER CONNECTIONS

22. It is customary, on switchboards, to make one voltmeter answer for several machines or circuits by providing

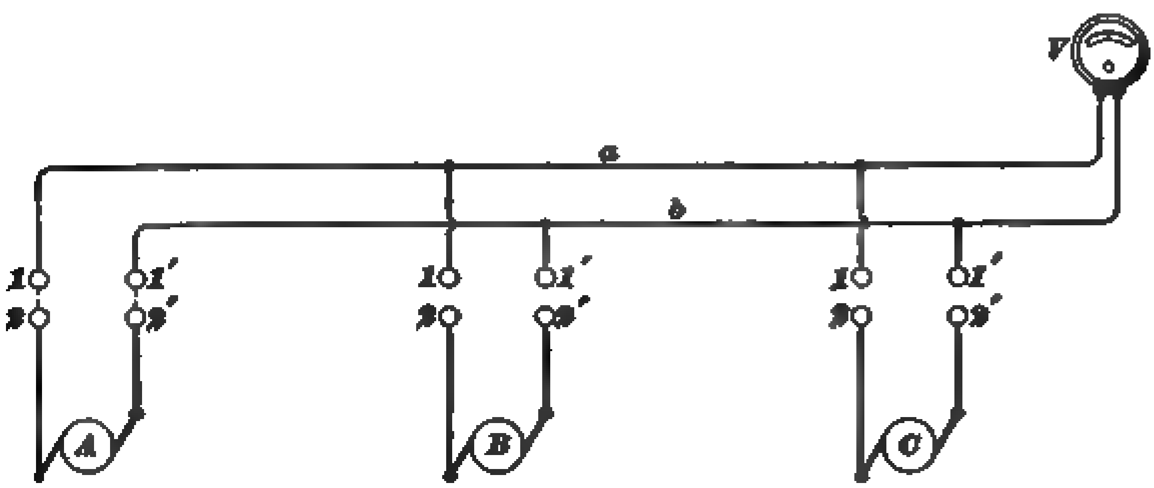


FIG. 21

suitable voltmeter plugs or a voltmeter switch by means of which the instrument can be connected to the circuit or

machine on which a voltage reading is desired. Figs. 21 and 22 show a common plugging arrangement. A pair of voltmeter bus-wires *a*, *b* are connected to the voltmeter *V*, Fig. 21, and taps connect from *a*, *b* to the plug receptacles *1*, *1'*. The different dynamos are connected to *2*, *2'* and when a voltmeter reading is desired on, say, machine *A*, a plug, Fig. 22, is inserted into the receptacle, thus connecting *1*, *2* and *1'*, *2'*.

FIG. 22

23. Pressure Wires.—In many cases, particularly on systems supplying current for lighting purposes, it is necessary to know the pressure at the point where the current is utilized rather than at the station. In some cases, especially on low-pressure, three-wire systems, *pressure wires a*, *b* are run back to the station, as shown in Fig. 23.

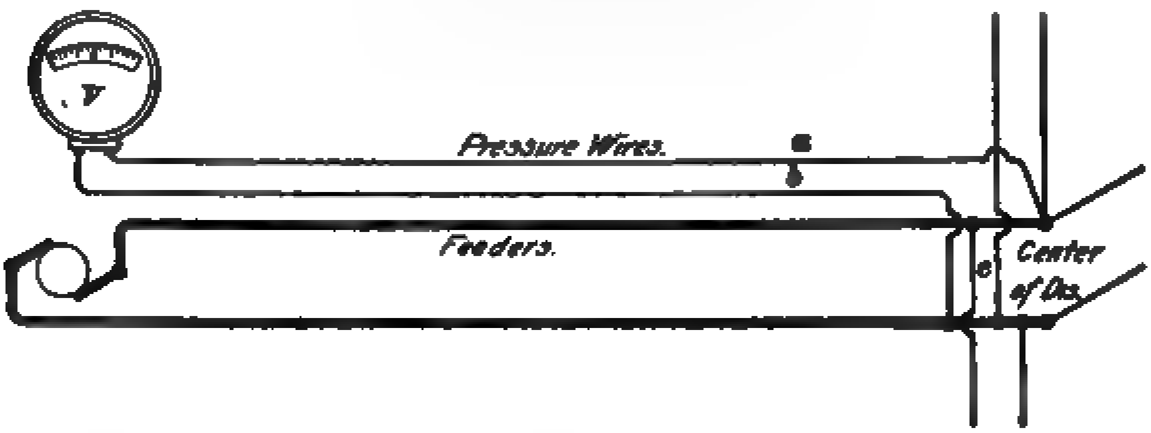


FIG. 23

The current required to operate the voltmeter is so small that there is practically no drop in the pressure wires; they can, therefore, be of small cross-section (usually No. 8 or No. 10 when strung on poles); insulated iron wire is sometimes used for the purpose.

24. Compensating Voltmeter.—In order to avoid the use of pressure wires, *compensating voltmeters*, or *compensators*, are sometimes used with alternating-current circuits. The **compensator** is a device used in connection with the voltmeter to decrease the voltmeter reading as the load

increases, by an amount proportional to the drop in the line. The attendant then increases the field excitation of the alternator and brings the pressure up to such an amount that the voltage at the distributing point is correct.

Fig. 24 shows the connections for one of the earlier types of Westinghouse compensating voltmeter. It consists of a series-transformer with both primary and secondary coils wound in sections. The primary is in series with the main circuit, and the secondary connects to a small auxiliary coil *c* on the voltmeter in such a manner that the current in *c* opposes the action of the current in the regular voltmeter coil *d* that

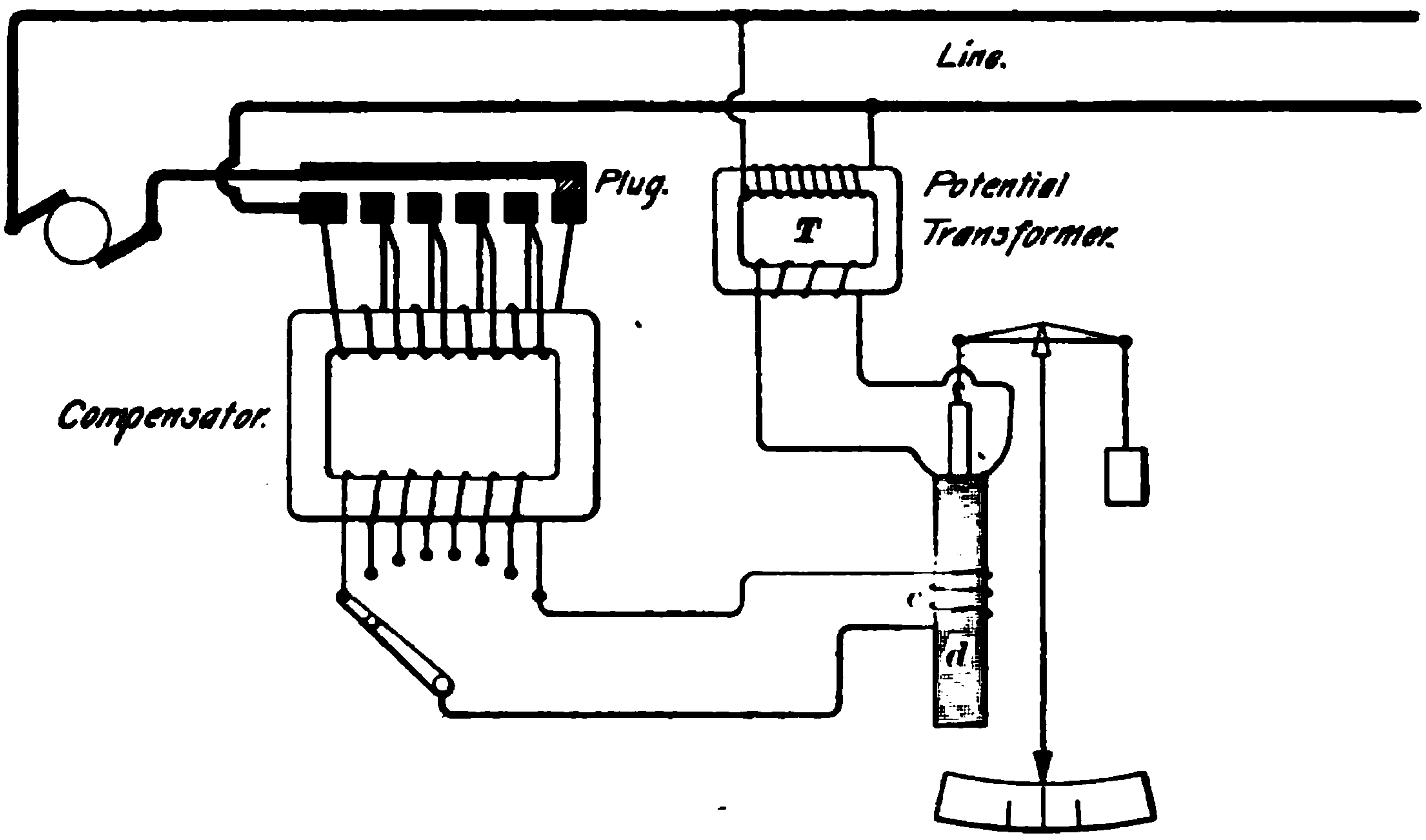


FIG. 24

is fed from the small potential transformer *T*. When the voltage at the distributing end of the line is at its correct value, the hand of the voltmeter indicates the standard voltage. When the load increases, the current through the primary of the compensator also increases; this, in turn, increases the current in the secondary and the auxiliary coil. The hand on the voltmeter, therefore, goes back, and the pressure must be raised to bring it back to the standard point. By plugging in at different points on the primary and by setting at different points on the secondary, the compensator may be adjusted for operation on almost any of the circuits

ordinarily met. After it is once set to suit the particular line on which it is to work, it requires no further attention.

25. The Mershon Compensator.—The compensator just described answers very well for lines that have little self-induction and that supply a non-inductive load. Where, however, the load is inductive, as, for example, a load of motors or of motors and lamps, the reactance of the line may have a very great influence on the drop in voltage, and the compensator must compensate not only for the ohmic drop in the line, but also for the drop due to the reactance. The **Mershon compensator,** brought out by the Westinghouse Company, is designed to accomplish this.

26. The principle of this compensator is briefly as follows: The E. M. F. supplied at the end of the line is always equal to the resultant difference between the E. M. F. generated and the E. M. F.'s necessary to overcome the resistance and reactance. If, then, three E. M. F.'s are set up at the station that are proportional to the above three E. M. F.'s and bear the same phase relation with regard to one another, and if these E. M. F.'s are combined in the same way as the line E. M. F.'s, it is evident that their resultant will make the voltmeter indicate the E. M. F. at the end of the line. For example, take the simple case shown in Fig. 25 (*a*). *A* is an alternator supplying current to the line. T' is an ordinary potential transformer, the secondary of which gives a voltage proportional to the generator voltage and in step with it. If the voltmeter *V* were connected directly to T', it would evidently indicate the station voltage, but what is wanted is an indication of the voltage at the far end of the line, and in order to get this, the voltage of T' must be reduced by an amount equal to the sum of the drops caused by the reactance and resistance. An adjustable reactance *a* and an adjustable resistance *b* are therefore inserted in the circuit. The drop through *b* will be proportional to and in phase with the resistance drop, and the voltage across *a* will be proportional to and in phase with the inductive drop. From the way in which the connections are

made, it is easily seen that the voltage acting on V is a combination of the voltages of T', a, and b. The drop across a and b will increase as the current in the line increases;

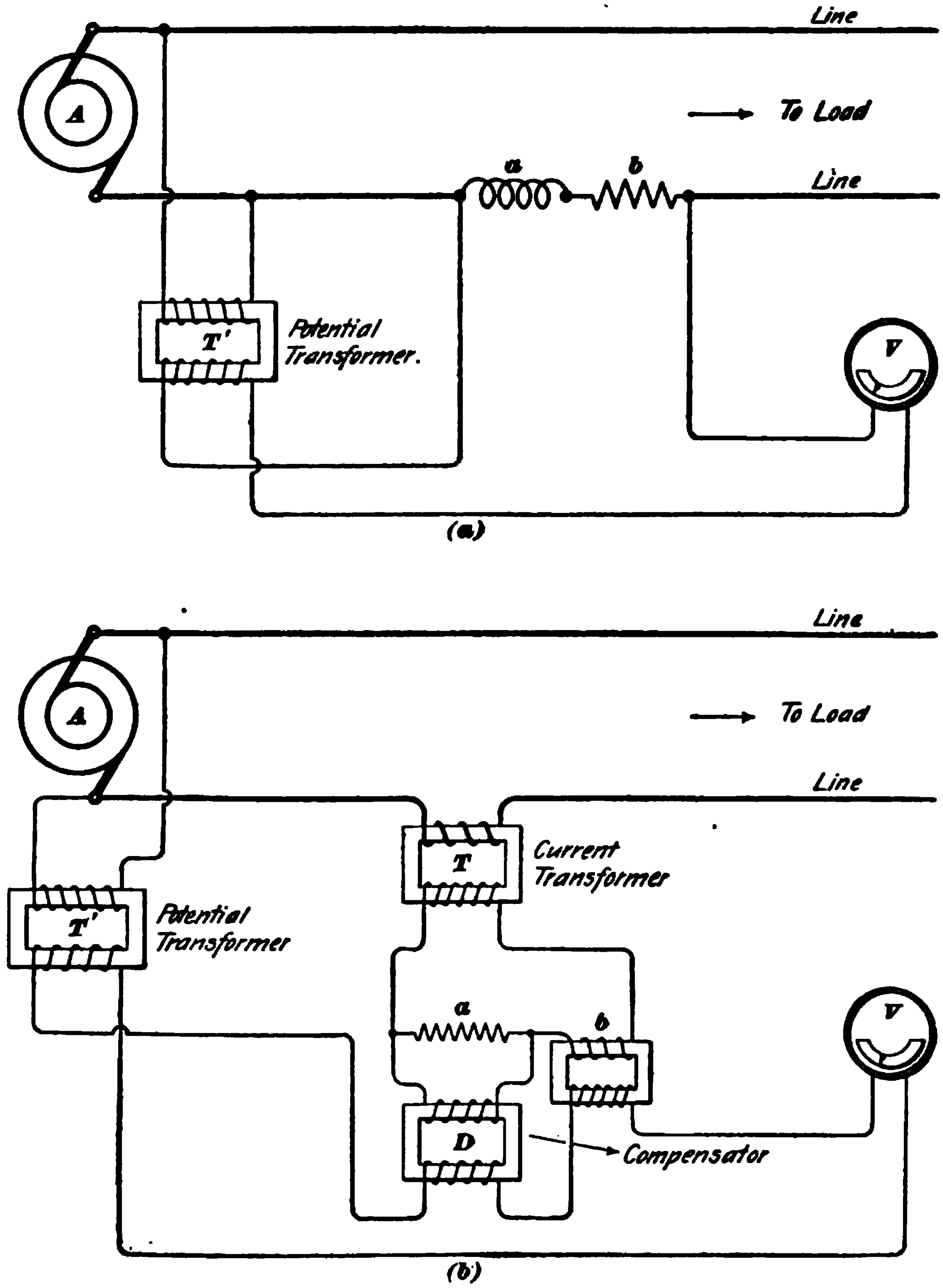


FIG. 25

hence, the voltmeter reading will decrease (because the connections are made so that the pressures across a and b cut down the E. M. F. applied to V). The voltmeter will,

therefore, indicate the true pressure at the end of the line because both the ohmic and inductive drops are accounted for.

Fig. 25 (*a*) is intended to illustrate the principle only; the actual connections are more nearly as indicated in Fig. 25 (*b*). Here *A* is the alternator, as before, and *T'* the potential transformer. *T* is a small current transformer, the primary of which is connected in series with the line and the secondary to the compensator proper, which consists of three parts, *a*, *b*, and *D*. The E. M. F. generated in the secondary of *T'* is proportional to and in step with the generator E. M. F. The current in the secondary of *T* is proportional to the load; *a* is a non-inductive resistance and *b* is a reactance coil wound on an iron core. These coils are connected in series, and the current supplied from the secondary of *T* passes through them. The E. M. F. across *a* is therefore in step with and proportional to the resistance drop in the line; while that across *b* is in step with and proportional to the back E. M. F. due to the reactance of the line. *D* is a small transformer in shunt with *a*; its secondary E. M. F. is in step with and proportional to the E. M. F. across *a*; *b* is also provided with a secondary that gives an E. M. F. in step with and proportional to the E. M. F. across *b*. All these devices, i. e., *a*, *b*, and *D*, are in one piece of apparatus, and terminals from the secondaries of *D* and *b* are brought out to two multipoint switches, so that the number of turns in each may be adjusted to suit different lines. For three-phase circuits, *a* and *b* are supplied from two series-transformers whose primaries are connected in series with two of the lines and whose secondaries are in parallel. The voltmeter compensator made by the General Electric Company operates on practically the same principle.

FUSES AND CIRCUIT-BREAKERS

27. Either *fuses* or *circuit-breakers* may be used to protect the generators or circuits from an excessive flow of current, due either to a short circuit or overload. Fuses are not used as much as they once were, as it has been found that circuit-breakers are more reliable. The

circuit-breaker may be a separate device, or the main switch may be provided with an automatic tripping device, as already described.

FUSES

28. A **fuse** consists of a strip or wire of fusible metal inserted in the circuit, and so proportioned that it will melt and open the circuit if the current for any reason becomes excessive. Fuses are often made of a mixture of lead and bismuth, though copper and aluminum are also used. Aluminum is used very largely for high-tension fuses.

For low-tension switchboards, plain open fuses may be used; but for high-tension work, it is necessary to have them arranged so that the arc formed when they blow will not hold over. Moreover, it is necessary to have high-tension fuses arranged so that they can be renewed without danger to the switchboard attendant.

29. Fig. 26 (*a*) shows a type of fuse block used by the General Electric Company on alternating-current switchboards; (*b*) shows the shape of the aluminum fuse used in the block. The fuse holder is made in two parts, the lower part *A* being of porcelain and the upper part *B* of lignum vitæ. The lower part is provided with blades *c* that fit between the clips *d*, *d'*, in the same way as the blades of a knife switch. These clips lie in slots in the marble board *F* and are connected to the line and dynamo by means of terminals *g* and *h*. By adopting this arrangement, the whole block may be detached from the board by simply pulling it straight out, thus pulling the blades out of the clips. The fuse is shown at *l*, and is clamped by means of the screws *m*, *n*. A vent hole *p* is provided in the lignum-vitæ cover, and the rush of air through this vent, together with the confined space, results in the suppression of the arc. This fuse block is suitable for currents up to 150 amperes at 2,500 volts. For higher pressures fuse blocks are used in which the fuse is pulled wide apart as soon as it blows, thus breaking the arc.

The use of the fuses on low-tension lighting switchboards

is not as common as it once was, their place being taken by the automatic circuit-breaker. Fuses are, however, used considerably on alternating-current boards and also for protecting individual circuits on low-tension, direct-current boards. They are not as convenient or reliable as circuit-breakers, because it takes time to replace them when they blow, and only too often they are replaced with a heavier fuse or even a copper wire, which is of scarcely any use as a protection. Again, fuses of the same size do not always blow at

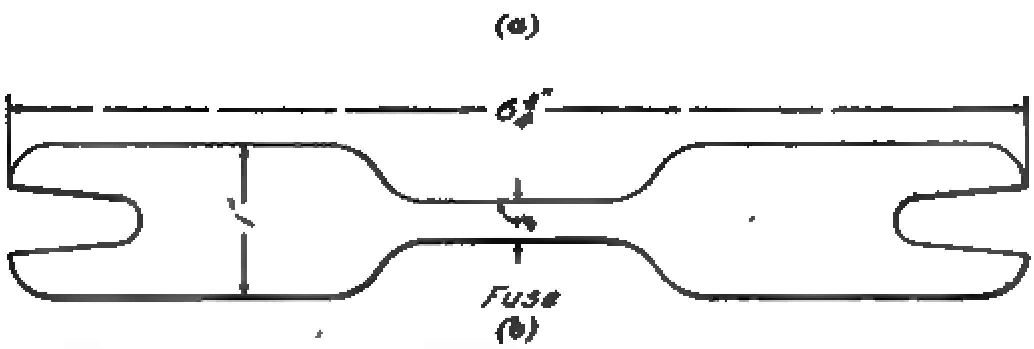


FIG. 26

the same current, as much depends on the nature of the fuse-block terminals. If the clamps are not screwed up tightly, local heating will result, and the fuse will blow with a smaller current than it should. Also, it has been found that a fuse of a given cross-section and material will carry a heavier current when the distance between the terminals is short than when it is long, on account of the conducting away of the heat by the terminals.

30. Fig. 27 shows a type of high-tension enclosed fuse made by the Stanley Electric Company. The fuse is held in the holder *a*, which can be pulled out of the clips *b* when a

fuse is to be renewed. Suitable blades are provided at each end to engage with clips *b*. The clips and connecting studs are thoroughly insulated by the porcelain insulators *c*, *c*, which prevent leakage of current to the supporting panel *d*. The fuse *h* passes through a fiber tube *e* and is held at each end by screws *i*; tube *e* is enclosed in the hard-rubber tube *f* of large diameter. At each end of the fuse is a cavity in which

FIG. 27

is placed a carbon ball *g*, and when the fuse blows the balls are forced up against the openings leading to the terminals, thus cutting off the arc. These fuses can handle a current of 50 amperes at 20,000 volts. There is a small hinged lid *k* on top that is thrown up when the fuse blows, and thus acts as an indicator to show which fuse has blown.

The high-tension fuse used by the Westinghouse Company consists of two long hinged wooden arms that are held together by the fuse against the action of a spring. As soon as the fuse melts, the arms separate, thus placing a break of several feet in the circuit and rupturing the arc.

CIRCUIT-BREAKERS

31. Some circuit-breakers have already been described in connection with high-tension switches. The **circuit-breaker** is essentially an automatic switch that opens the circuit whenever the current exceeds the allowable limit. It is therefore intended more as an automatic safety device than as a switch for regularly opening or closing the circuit.

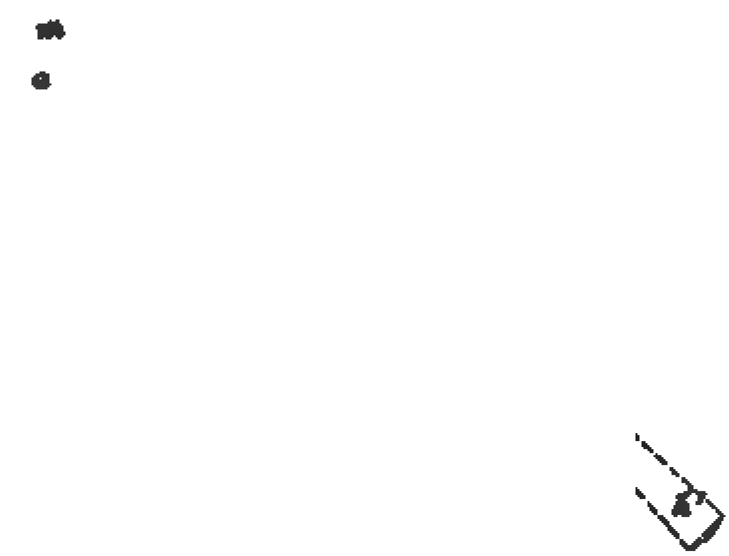


FIG. 23

Circuit-breakers are made in great variety, handling currents from a few amperes up to several thousand, and are constructed for both alternating current and direct current. In nearly every case they consist of a switch of some kind that is held closed against the action of a spring. The main current passes through an electromagnet or solenoid, and when the current for which the breaker is set is exceeded, this magnet attracts an armature or core and operates a trip, thus allowing a switch to fly out. In some cases the breaker

opens both sides of the line, though often they are single-pole and open one side only. We will illustrate here a few examples to show their general method of operation.

32. General Electric Circuit-Breakers.—Figs. 28 and 29 show a type of **General Electric circuit-breaker** designed for 125- or 250-volt circuits. One of the principal features of this circuit-breaker is the main contact used. It consists of a U-shaped laminated contact *a* which is pressed firmly against the contacts *b*, *b* by means of a togglejoint, when handle *h* is forced down. Each main contact is provided with a pair of light auxiliary contacts *m*, *m* that can be easily renewed. These wipers press against the carbon blocks *p*, *p*, and when the breaker flies out, the arc is finally broken between the carbon blocks and the wipers. Laminated contacts are not liable to stick and they make a very good contact because of the firm pressure and the slight wiping action caused by the closing of the breaker. The tripping coil *S* attracts the armature *A* when the current becomes excessive and trips the breaker, which is promptly opened by the spring *t*. The current for which the breaker is set may be adjusted by means of the screw *v* and the breaker may be tripped by hand at any time by pulling down on the knob *w*. The breaker shown in Fig. 28 is a double-pole; Fig. 29 shows a similar breaker of the single-pole type.

Fig. 29

33. General Electric M K Circuit-Breaker.—This breaker, Fig. 30, has been very widely used for 500-volt, direct-current, railway switchboards and is here shown as an example of the class of circuit-breakers in which a magnetic field is used to extinguish the arc. In Fig. 30, *B* is a heavy tripping coil through which the main current passes. The

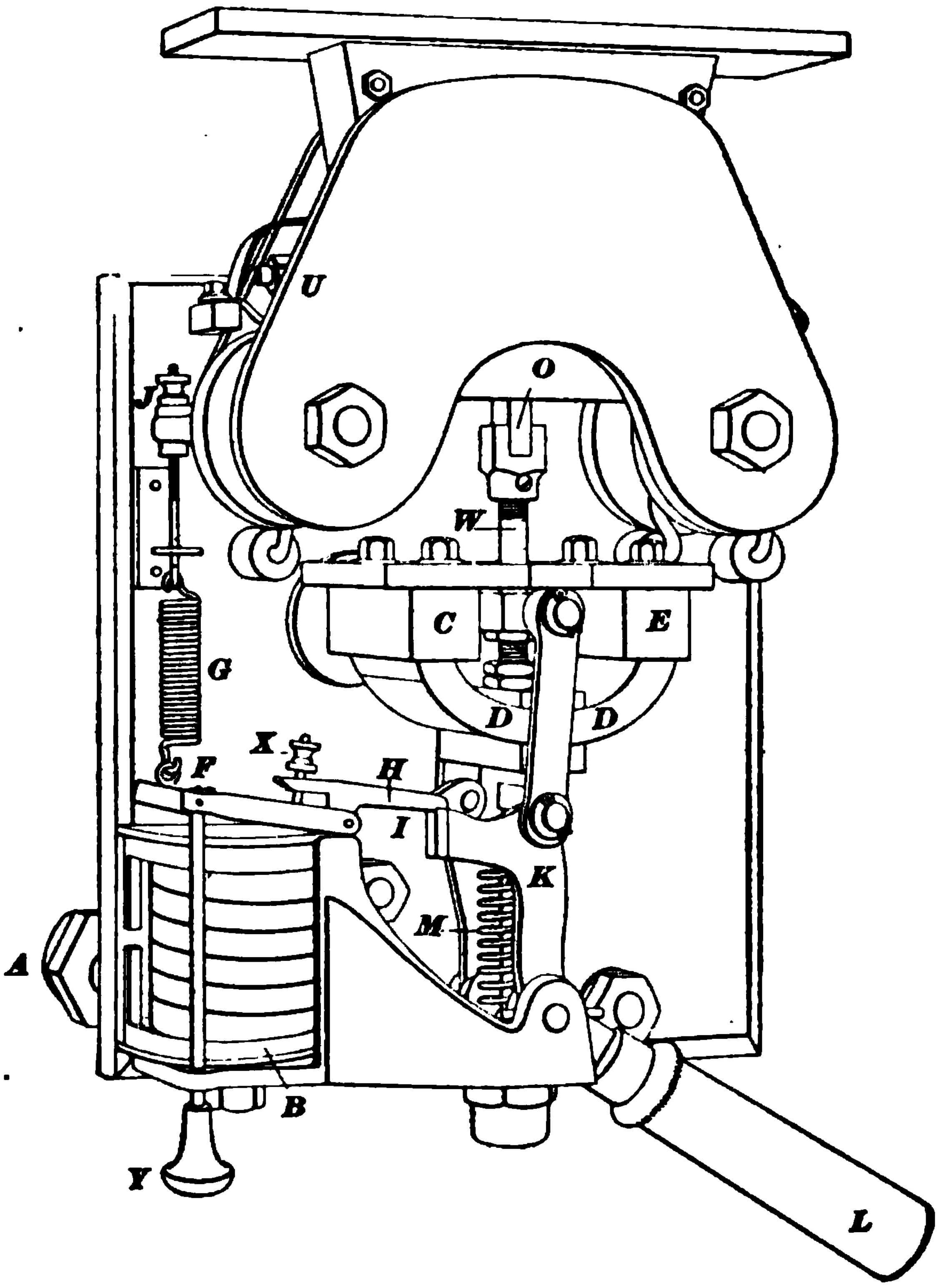


Fig. 30

current enters the coil through the stud *A*; from the coil it passes to a connection on the back of the heavy copper contact block *C*. When the breaker is closed ready for service, as shown in the figure, the main current passes from *C* to the laminated contact *D*, *D* and out to the line through the heavy block *E*, which has a terminal like *A* in the rear.

When the breaker is closed, the hinged iron armature F is held up by a spring G, the tension of which depends on the adjustment of a thumbscrew J. Attached to plate F is a trigger H, that has a shoulder against which a projection on the main handle yoke K bears. To set the breaker, the main handle L is pulled down hard; this forces D, D up against blocks C and E, and also causes the projection on K to engage trigger H, which holds the circuit-breaking parts in place. In setting the switch, spring M is extended. When the breaker trips, solenoid B draws down armature F, and with it trigger H, which liberates the switch yoke and allows

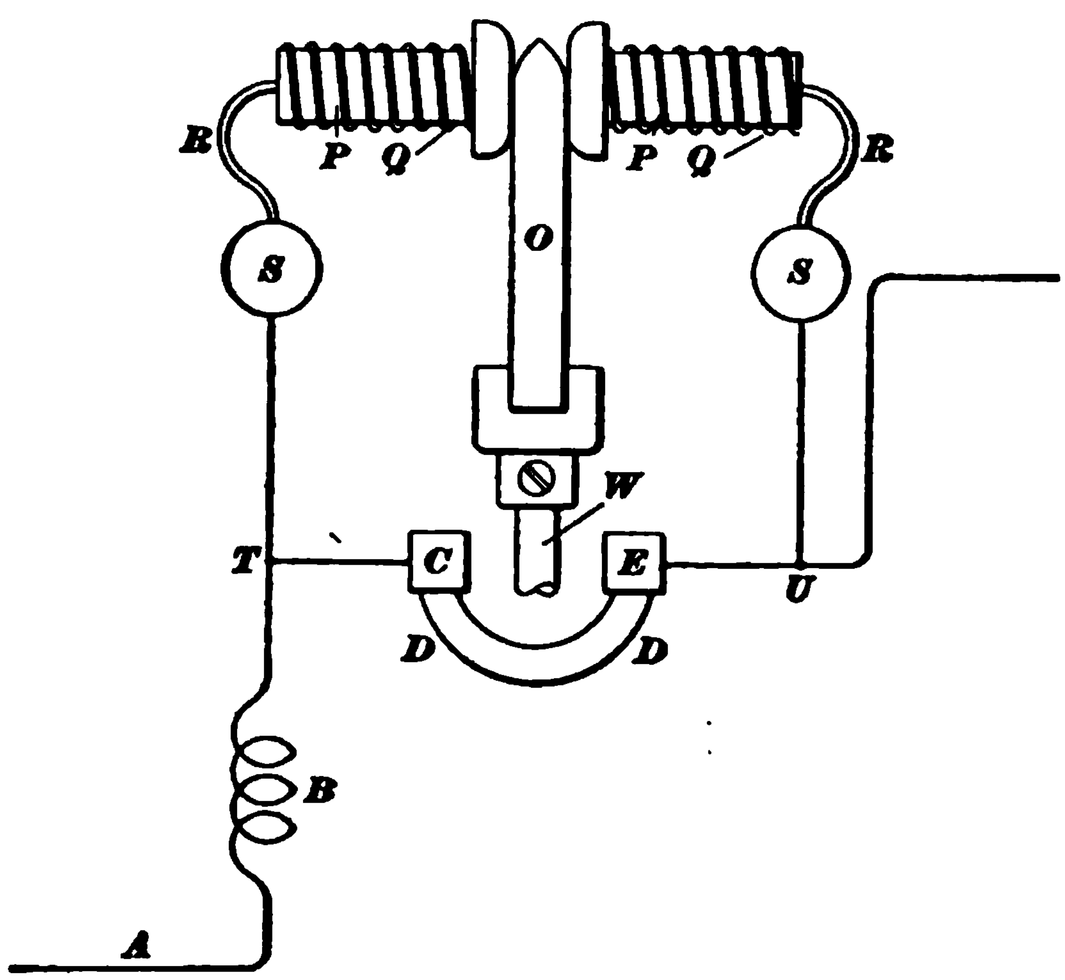


FIG. 31

the strong spring M to pull down D, D, and hence open the circuit at C and E. In order to prevent burning of the main contacts, a shunt path is provided, as indicated by the circuit T-S-R-P-O-P-R-S-U, Fig. 31. S, S are two magnetizing coils that set up a strong magnetic field between the auxiliary contacts P, P. When the breaker is closed, the contact piece O is pushed up between contacts P, P which are pressed firmly against O by springs Q, Q. When the breaker trips, contact D, D leaves C, E a little

before O leaves P, P, so that for a short interval the main current takes the path through the auxiliary contacts and blow-out coils S, S. A strong magnetic field is thus set up and when the circuit is finally broken at the auxiliary contacts, the arc is instantly blown up through an opening in the top of the breaker. Whatever burning action there may be is thus transferred to the auxiliary contacts, which are easily renewed or repaired.

34. Cutter Circuit-Breaker.—Fig. 32 shows the **Cutter (I. T. E.) laminated-type circuit-breaker.** The main contact *a* is laminated and is pressed against the contact surfaces by means of the handle working through a togglejoint at *c*. The tripping coil is shown at *d* and when the current exceeds the amount for which the breaker is set the core inside *d* is suddenly drawn up, thus striking a trigger and allowing the breaker to fly out. The position of the core in *d* can be changed by adjusting screw *e*, thereby varying the current at which the breaker trips. Auxiliary carbon contacts *b*, *b* do not open until after the main contact so that the burning action is confined to the carbon contact surfaces. The Westinghouse circuit-breakers are very similar in general appearance and operation to the type shown in Fig. 32, the main difference being in the arrangement of the tripping coil.

Fig. 32

GROUND DETECTORS

35. Ground detectors are used to determine whether or not a line or conductor, that should normally be insulated, is in contact with the ground or any conductor leading to the ground. A voltmeter makes a very good ground

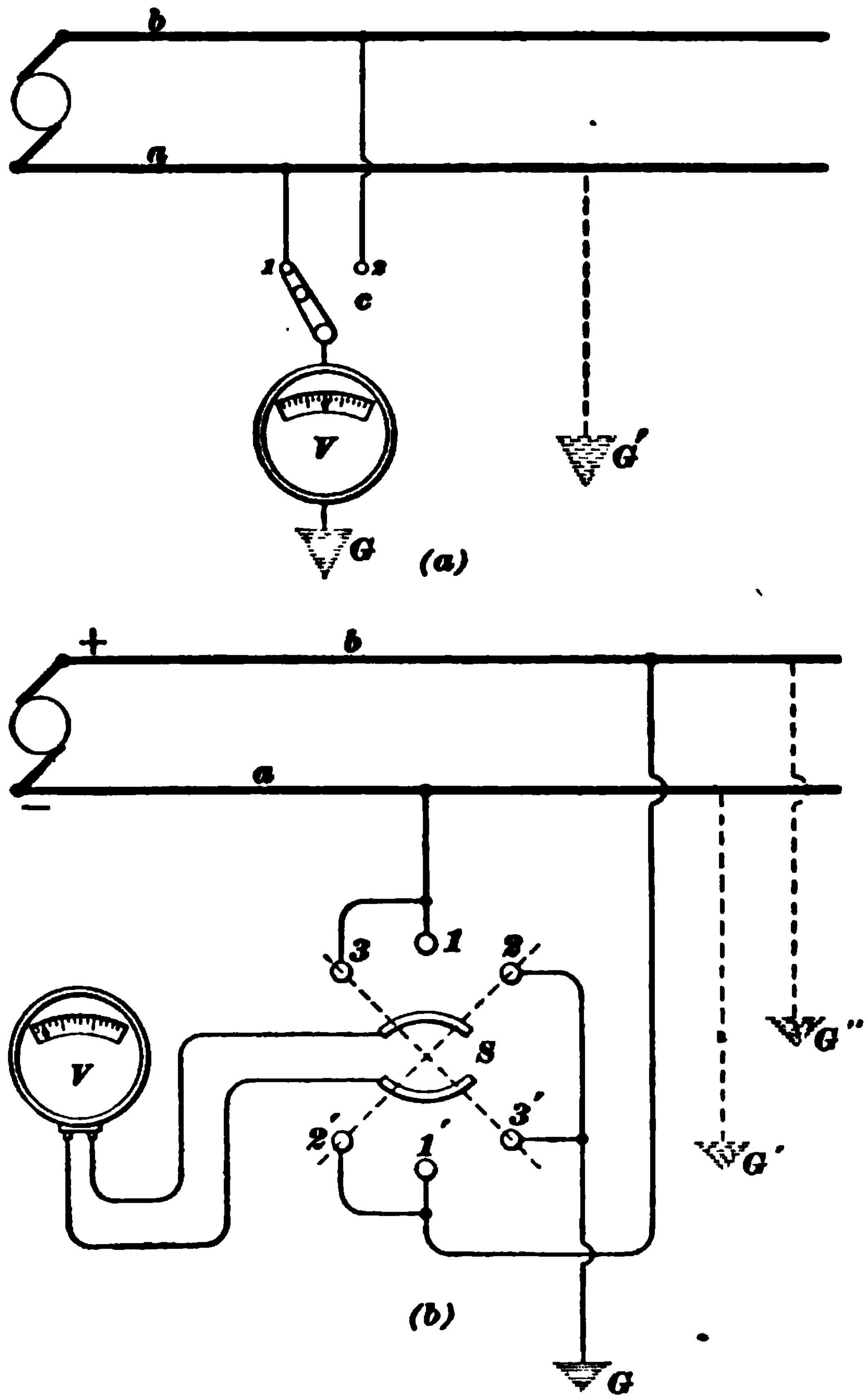


FIG. 33

detector, because it not only indicates whether a ground is present, but by its deflection it shows whether the path of the current to ground is one of high resistance or low resistance.

In order to indicate grounds, the voltmeter may be connected as shown in Fig. 33 (*a*). If the line *a* should be grounded, as indicated by the dotted line, and the switch blade placed on point *1*, no deflection would result. If, however, the blade is moved to point *2*, current will pass from line *a* through the ground on the line to the voltmeter to point *2*, and thence to the line *b*, thus completing the circuit. When a deflection is obtained on point *2*, it shows that line *a* is grounded; and when obtained on point *1*, it shows that line *b* is grounded. If the ground is of high resistance, the deflection will be comparatively small; if of low resistance, the deflection will be large. In Fig. 33 (*a*), the current will flow through the voltmeter in the opposite direction on point *2* from what it will on point *1*; hence, the voltmeter must have its zero point in the center of the scale, so that it can read either way. Voltmeters, however, have their zero point at the left-hand end of the scale, and it is convenient to have a switch that will allow the ordinary voltmeter to be used either as a voltmeter or ground detector. Fig. 33 (*b*) shows an arrangement for doing this. When the switch is in the position *1–1'*, the voltmeter *V* is connected directly across the line and gives the voltage on the system; when in the position *3–3'*, the voltmeter indicates any grounds, such as *G''*, that may be present on line *b*. When *S* occupies the position *2–2'*, *V* indicates grounds on line *a*, as at *G'*.

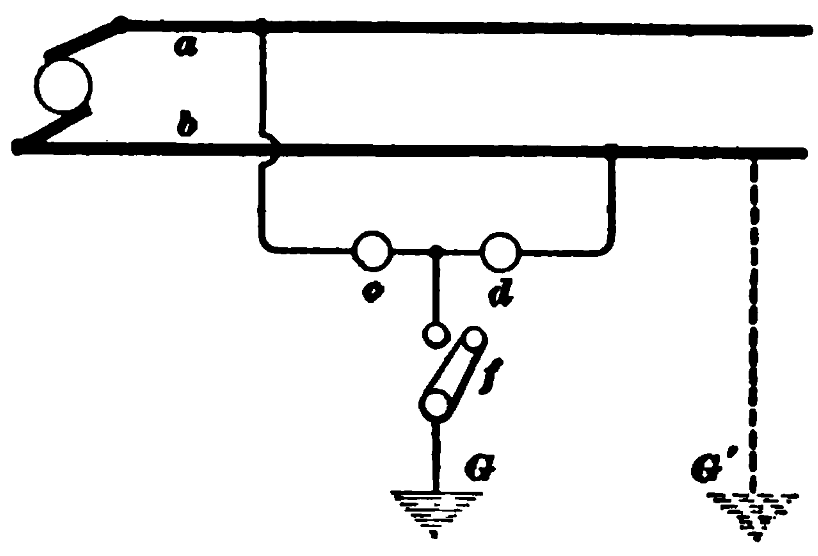


FIG. 34

36. Another very common arrangement for detecting grounds is shown in Fig. 34, where two lamps *c*, *d* are connected in series across the lines. The voltage for which these lamps are designed is equal to that of the dynamo, so that when the two are connected in series, they will burn dull red. At the point between the lamps, a connection is

made to ground through a switch or a push button *f*. If contact is made at *f* and there is no ground on either line, the brilliancy of the lamps will not be altered. If there is a ground on *b*, as indicated at G', lamp *d* will go out when switch *f* is closed, and *c* will burn brightly. This lamp detector is simple, and while it serves as an indicator of grounds, it is not as satisfactory as the voltmeter detector, as it does not give accurate indications as to the resistance of the fault.

37. Fig. 35 shows a lamp ground detector suitable for a three-wire, low-tension system. Three lamps l_1, l_2, l_3 are connected in series across one side of the system, and a ground connection is made at *x* through key *K*. When all three lines are clear of grounds, the lamps will burn at a dull red, they will all be equal in brightness, and their color will not change when key *K* is pressed. If line *C* becomes grounded at G', then, when *K* is pressed,

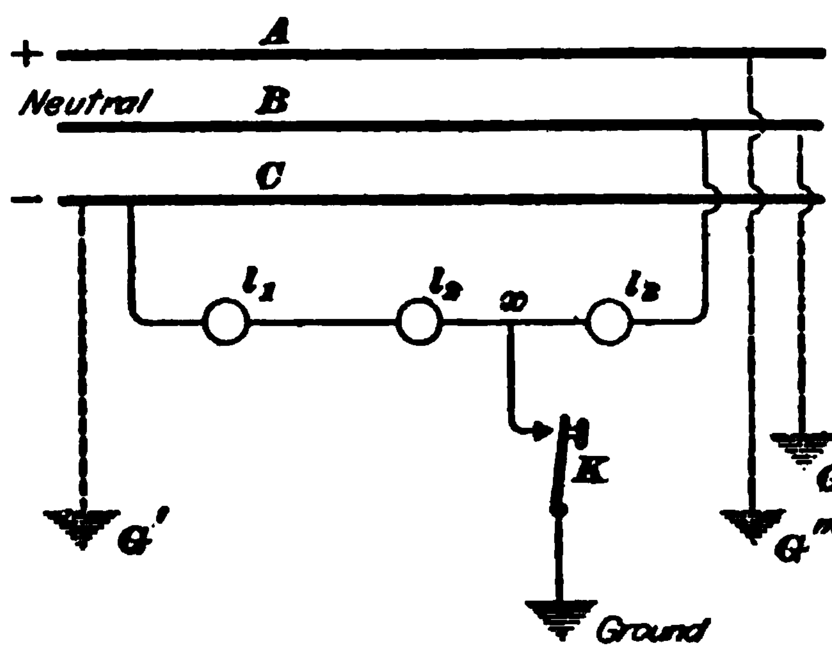


FIG. 35

l_1 and l_2 will go out, and l_3 will come up to full candlepower. If a ground occurs at G'' on line *B*, lamp l_3 will go out and l_1, l_2 will brighten up, but will not come up to full candlepower because two of them will be in series between *B* and *C*. If there is a ground at G''' on line *A*, all the lamps will come up to full candlepower, because they will all get the full voltage, l_3 being across *A B* and l_1, l_2 in series across *A C*.

38. The ground detectors just described apply more particularly to low-tension, direct-current installations, but similar arrangements may be adapted to high-tension, alternating-current systems by using potential transformers. Fig. 36 shows one method used by the Westinghouse Company on their alternating-current switchboards. The regular

voltmeter *V*, with which the switchboard is equipped, is here used also as a ground detector. *P* is a plug switch by means of which points *1* and *2* or *1* and *3* may be connected together. Under ordinary conditions, the plug is in *1* and *2*, thus connecting the primary of the potential transformer across the line, and *V* serves as an ordinary voltmeter. *S* is a key that connects one side of the line to ground through the transformer primary. If there happens to be a ground on the side *b*, as shown at *G'*, the voltmeter will give a reading when *S* is pressed. By placing the plug in points *1* and *3*, side *a* may be tested. When the key *S* is not pressed, the lever *5* is against contact *4*, so that *V* is connected as an ordinary voltmeter.

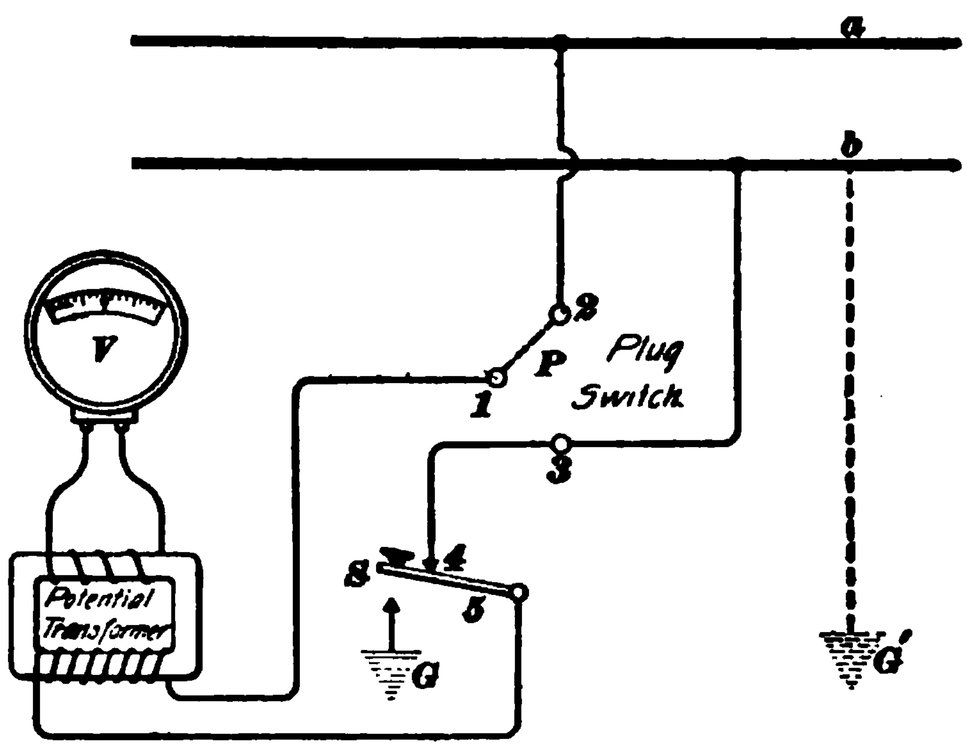


FIG. 36

39. Electrostatic Ground Detectors. — Ground detectors operating on the electrostatic principle are much used on high-pressure, alternating-current switchboards. They have the advantage that they require no current for their operation and may be left connected to the circuit all the time, thus indicating a ground as soon as it occurs. They also give an indication without its being necessary to make an actual connection between the line and ground, as is the case with all the detectors previously described. Fig. 37 illustrates the principle of a Stanley electrostatic ground detector, which is especially adapted to high-pressure, alternating-current lines because the instrument is not in actual connection with either of the lines. The fixed vanes *1* and *4*,

2 and *3* are connected together in pairs, as shown. The movable vane *V* is connected to the ground and is held in the central position shown in the figure by means of small spiral springs *S*. The pairs of fixed plates are not connected direct to the lines, but are attached to plates *a*, *a'* of two small condensers which consist simply of two brass plates, mounted in hard rubber but separated from each other.

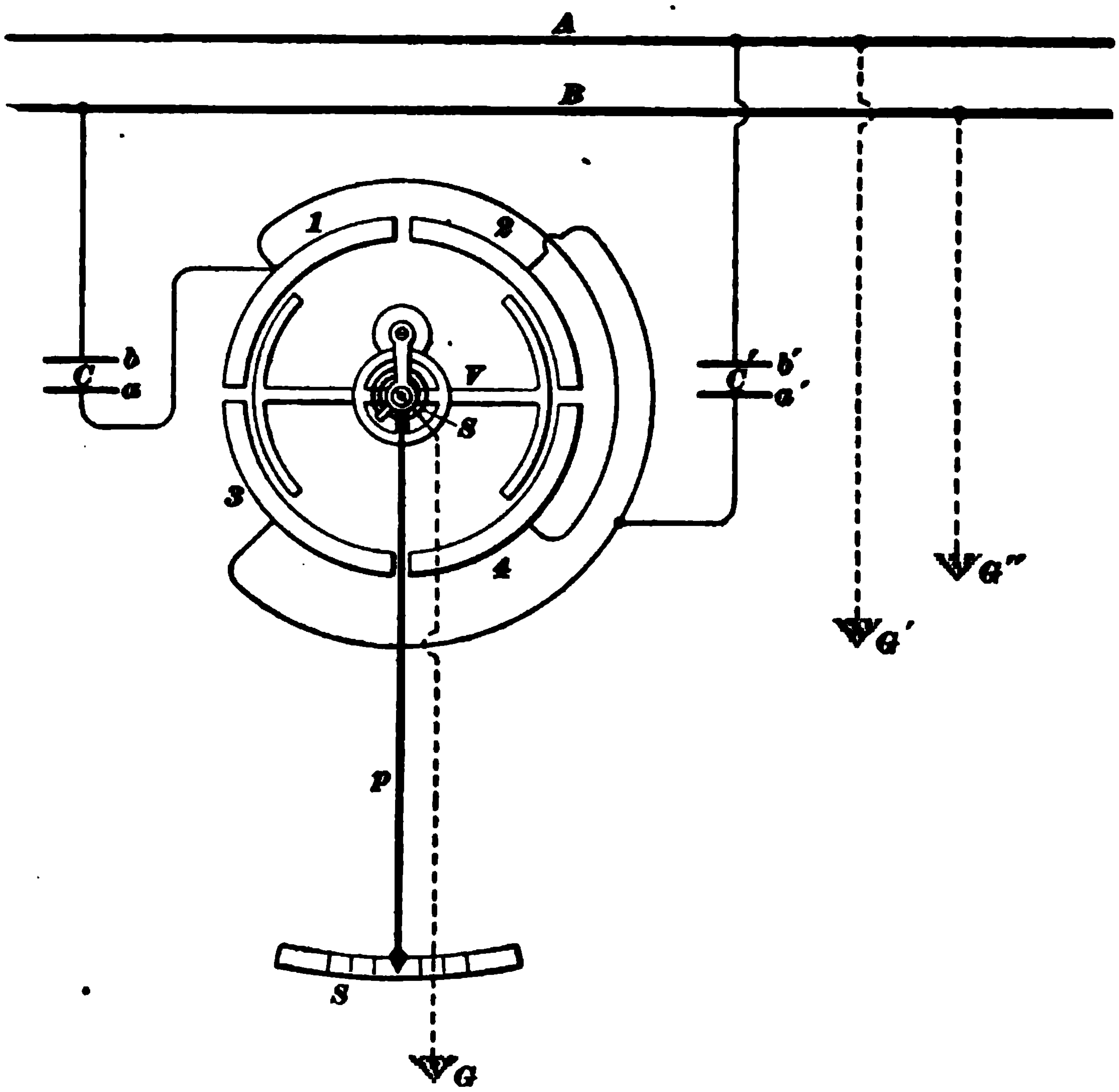


FIG. 37

Plates *b*, *b'* are connected to the lines. When no grounds are present, *1* and *4*, *2* and *3* become oppositely charged by reason of charges induced on plates *a*, *a'* by plates *b*, *b'*. The forces acting on the vane *V* are therefore equal and opposite. Now, suppose that line *B* becomes grounded at *G''*. This is equivalent to connecting vane *V* to line *B*; *V* takes up a charge similar to *2* and *3*; hence, it is repelled by *2* and *3*

and is attracted by *1* and *4*, thus giving a deflection. If *A* becomes grounded, a deflection in the opposite direction is obtained. Instruments of this kind can, of course, only be used in places where the pressure is fairly high, as the electrostatic forces produced by charges due to low pressures would not be large enough to operate an instrument unless it were made much too delicate to be of practical use in a light or power station. In most electrostatic detectors, the lines are connected directly to the fixed sectors *1*, *2*, *3*, *4* and the condensers *C*, *C'* are omitted.

FIG. 38

40. Fig. 38 shows an electrostatic ground detector made by the Wagner Electric Company. The fixed quadrants are shown at *a*, *a*, and the movable vane at *b*, *b*. The quadrants are connected to the line wires, and the vane is connected to ground. The vane is held normally in its central position by means of a spring, and the pointer is deflected whenever a ground occurs on either line. The principle of action is the

FIG. 39

same as that of the electrostatic ground detector just described.

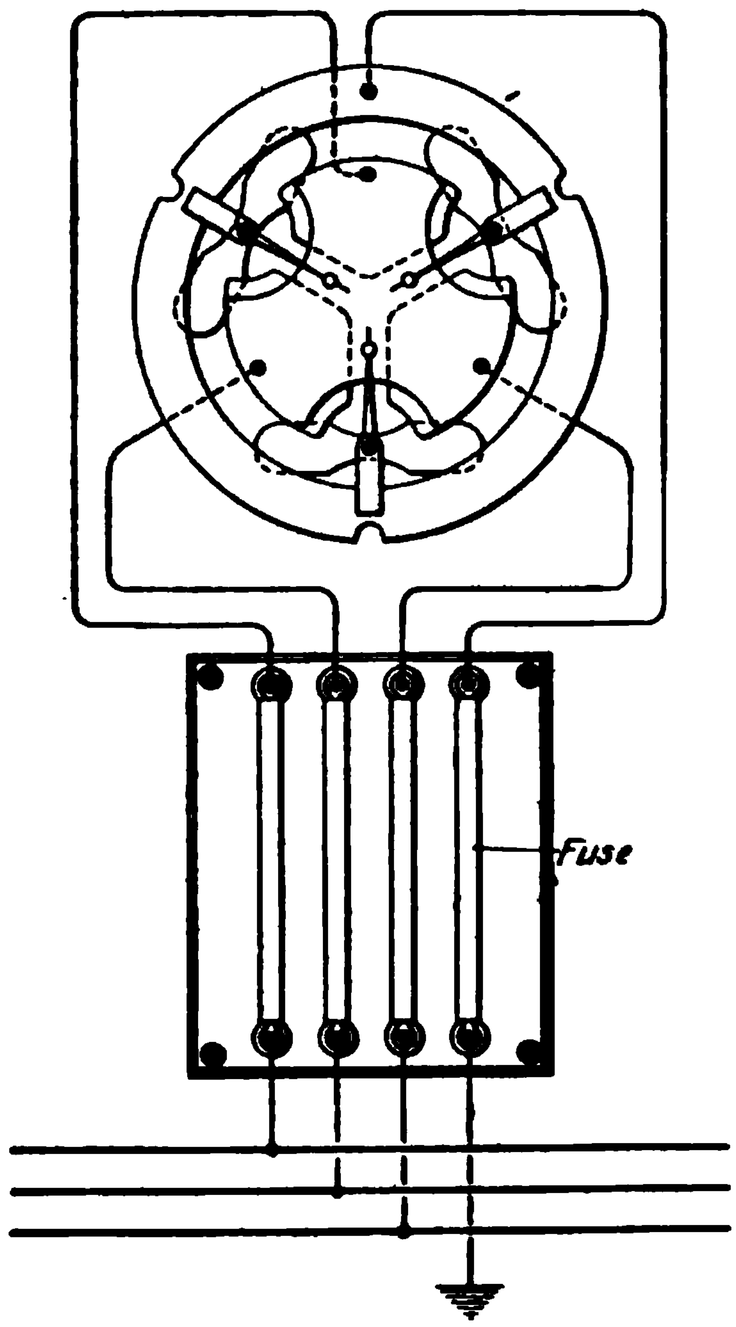


Fig. 40

41. Figs. 39 and 40 show a General Electric, three-phase, electrostatic ground detector. It is practically three single-phase detectors combined in one instrument. When no ground exists, the three needles point toward the center. When a ground occurs on one of the lines, the two adjacent needles are deflected toward the segments to which the grounded line is connected. Should a ground occur on two lines, the needle between the segments connected to the grounded lines will be deflected toward the one having the lower resistance ground and the two remaining needles will be deflected toward the grounded segments.

POTENTIAL REGULATORS

42. Where a number of feeders are supplied from a single dynamo or set of bus-bars, it is often necessary to provide means for raising or lowering the pressure on these feeders independently of each other. When alternating current is used, the pressure on the feeders can be easily adjusted by using **potential regulators.** These appliances, while not usually placed on alternating-current switchboards, are so closely connected therewith that they are here described. There are many types of regulators but they all take the form of a special type of transformer with the primary connected across the mains and the secondary in series with one of the mains.

43. Use of Transformer to Raise Voltage.—An ordinary transformer connected as in Fig. 41 can be used to raise or lower the primary voltage by an amount equal to the secondary voltage of the transformer. When the double-throw switch is in the position indicated by the dotted lines, the primary is across the mains and the secondary in series with the lower main, thus adding 100 volts in this case or subtracting 100 volts if the connections be such that the secondary E. M. F. opposes the line E. M. F. When the switch is thrown to the right, the boosting transformer is cut out.

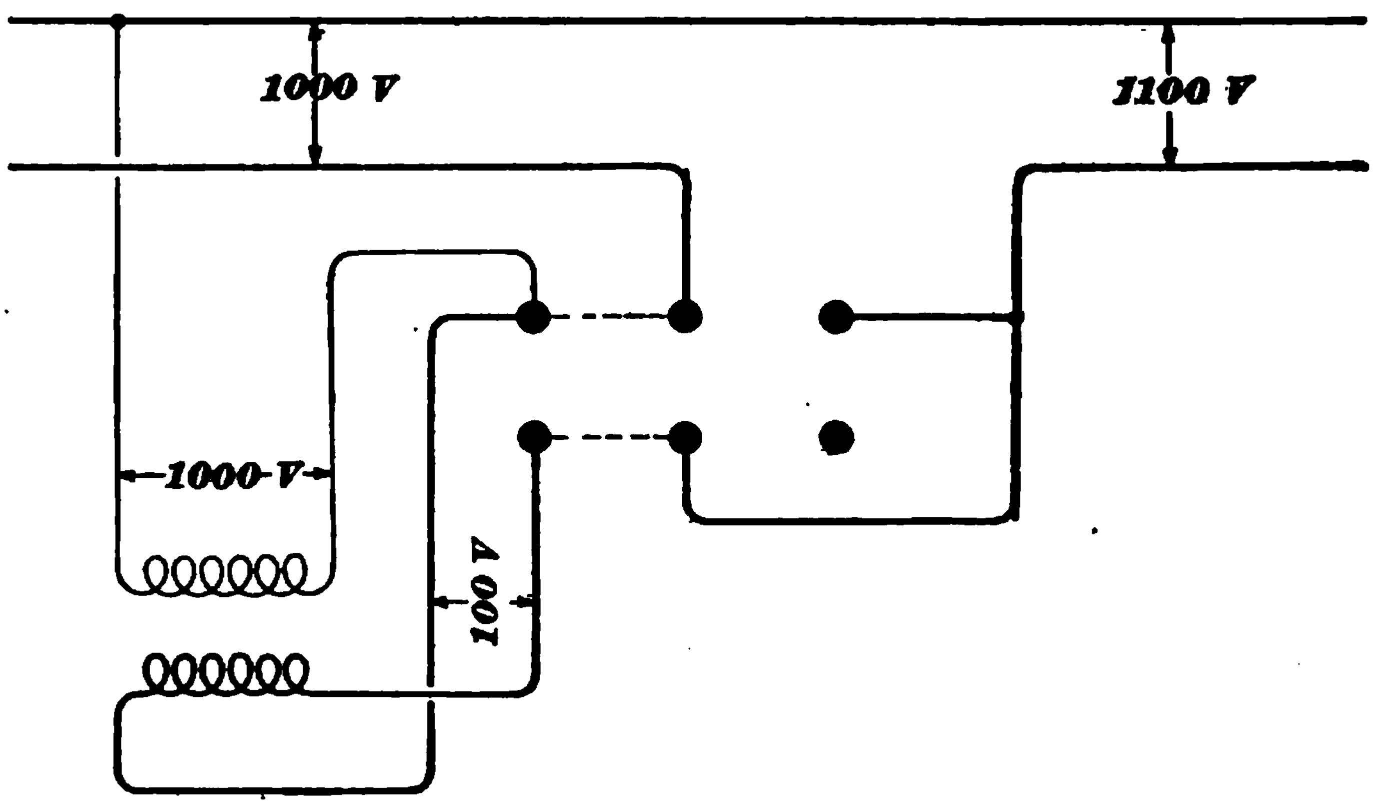


Fig. 41

44. Stillwell Regulator.—Fig. 42 shows the connections for a **Stillwell regulator.** It operates in the same way as the transformer in Fig. 41 but the secondary S is provided with a number of taps connected to a switch M so that the amount by which the voltage is raised or lowered can be adjusted. The primary P is connected to a reversing switch b so that the secondary E. M. F. can be made either to aid or oppose the primary E. M. F., thus using the regulator either to raise or lower the line pressure. The contact arm N is made in two parts, connected through a small reactance coil r, the object being to prevent momentary short-circuiting of the transformer sections during the instant the arm bridges over adjacent contact segments. By

following out the connections, it will be seen that the secondary is in series with the main circuit and the primary across the circuit, as in Fig. 41.

45. C R Regulator.—The **C R regulator**, made by the General Electric Company, operates in a manner very

Fig. 42

similar to the Stillwell regulator. Fig. 43 shows the general appearance of the regulator, and Fig. 44 the connections. The reversing switch operates automatically and is placed in the secondary circuit, and not in the primary as in the Stillwell

regulator. In Fig. 44 the reversing switch is indicated at the lower part of the figure, and consists of an arm that is moved by the arm of the main switch so as to connect *a* with either *c* or *b*. The windings consist of a primary and secondary, the former connected across the circuit, and the latter divided into a number of steps, in series with the circuit. When the reversing switch and the main switch arm are in the positions shown in Fig. 44, the main current flows through the whole of the secondary winding, and the maximum increase in voltage is obtained. As the dial switch arm is turned, the sections of the secondary are successively cut out as contact is made at *d*, *e*, *f*, etc.; when the arm reaches *g*, the whole of the secondary winding is cut out, and the voltage supplied to the feeder is the same as that furnished by the generator. When the arm is started on a second right-handed

FIG. 43

FIG. 44

revolution, the reversing switch is shifted automatically, so that point *a* is connected with *b*, and as the movement of the dial switch is continued to the right, the sections of the secondary are successively cut in, and the current now flows through them in the reverse direction to what it did before. The second revolution, therefore, lowers the feeder pressure below that of the generator; when the second revolution has been completed, the switch is automatically stopped. The dial switch is made so that when the handle is turned, springs are first compressed and the blade then unlocked by a cam so that it flies from one contact to the next almost instantly. The switch blade is slightly narrower than the distance between the contacts, so that there is no short-circuiting of the transformer sections.

46. A number of regulators are in use in which the voltage in the secondary is varied by changing the position of the secondary with regard to the primary, instead of cutting turns in or out. By having the secondary coil movable, it can be arranged so that the amount of magnetic flux passing through it can be varied, thus varying the amount of the pressure added or subtracted. In other regulators, both the primary and secondary coils are fixed, and a movable core arranged so that the magnetic flux passing through the secondary can be made to vary.

PROTECTION FROM LIGHTNING AND STATIC CHARGES

47. There are sources of danger to electrical equipments that may arise outside the station and that may cause great loss unless ample provision is made for protection. Among these are danger from lightning, danger from static charges, or other effects commonly referred to as *static*, and danger from short circuits caused by either of the former. Damage from lightning occurs on systems having overhead lines, but static charges and the damage resulting therefrom can occur on systems having either overhead or underground lines.

PROTECTION FROM LIGHTNING

48. Damage from lightning is due to an excessive difference of potential that may exist between the atmosphere and the earth, and as overhead electrical conductors offer a path of comparatively low resistance, the atmospheric electricity will seek such path to the earth, unless prevented by suitable methods of lightning protection. Any properly designed piece of apparatus should have sufficient insulation to withstand a potential considerably higher than that normally imposed on it, and to produce a ground, a lightning discharge must cause an excessive rise in the potential of the circuit. It frequently happens that the weakest point of insulation is at the switchboard or generator, and in the absence of sufficient protection, great damage will result at the station.

49. Overhead lines are always liable to accumulate a certain charge of static electricity even if they are not actually struck by lightning. Long transmission lines should be well protected against lightning, as they frequently run through exposed and mountainous country. If these high-pressure discharges travel along the line and get into the

dynamos at the power station, they are almost sure to puncture the insulation of the machines and cause a burn-out. To guard against this, *lightning arresters* should be provided.

50. Simple Lightning Arrester.—The term **lightning arrester** does not correctly express the use of these devices, because they do not arrest the discharge coming in over the line; they merely divert the charge by providing a path that the lightning will take to ground in preference to passing into the dynamo and making a path for itself to the ground by puncturing the insulation of the machine.

A lightning discharge is generally oscillatory in character, hence it will not pass through an inductive path if an

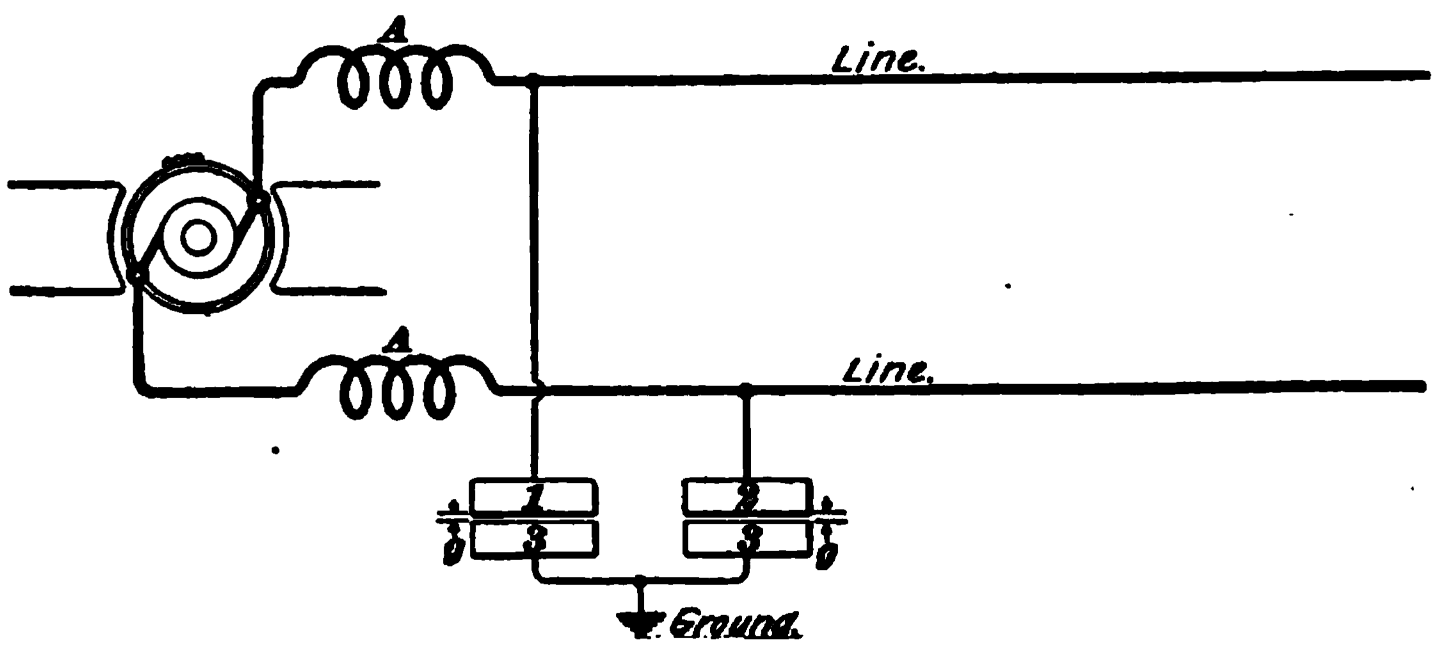


FIG. 45

alternative non-inductive path is provided for it. The object of a lightning arrester is to furnish a non-inductive path to ground and at the same time make provision for suppressing the arcing that usually follows a discharge. Fig. 45 shows a line equipped with lightning arresters of the simplest possible form. The plates *1*, *2* are connected to the lines and are separated by small gaps *g*, *g* from plates *3*, *3* which are connected to the ground. The gap in the arrester should be more easily jumped across by the discharge than the weakest insulation on the dynamo; otherwise, the discharge may jump through the insulation to the ground instead of jumping across the air gap. The air gap must, of course, be long enough so that the pressure generated by the dynamo

itself will not be able to jump across it. For pressures up to 500 volts, a gap of $\frac{1}{16}$ inch should be sufficient.

51. Reactance, or Choke, Coils.—In order to force the discharge to pass through the arrester, **choke coils, reactance coils,** or **kicking coils,** as they are variously called, are inserted between the arrester and the device to be protected. Such coils consist of a few turns of wire or copper strip connected in the circuit as shown at *A, A* in Fig. 45. The discharge, in preference to overcoming the inductance of these coils, will jump the air gaps and pass off to ground. Fig. 46 shows a typical reactance coil of small size suitable for low-tension work. Fig. 47 shows a Westinghouse choke coil made of flat copper ribbon and mounted on a heavy glass insulator. This coil is for use on a high-tension circuit; hence, thorough insulation from the ground is necessary.

FIG. 46

52. Suppression of Arcing.—The simple arrangement of air gaps shown in Fig. 45 would not be suitable for electric-light and power circuits for the following reason: If a discharge comes in over both the lines at once, as is quite likely to happen, because the lines usually run side by side, an arc will be formed across both the gaps, and current from the dynamo will follow the arc. This will practically short-circuit the dynamo, and such a large current will flow that the plates or contact points of the arrester will be destroyed. It is necessary, then, to have in addition to the air gap some means for suppressing or blowing out the arc as soon as it is formed. It is also necessary that as soon as the discharge has passed, the arrester will be in condition for the next discharge. Generally speaking, the arc from a direct-current machine is not as easily extinguished as that from an alternator; probably because every time the current passes through its zero value it loses some of its ability to hold the arc. In some cases, the arc is broken by being drawn out

until it can be no longer maintained; in others, the air gap is so placed that it will be surrounded by a magnetic field, so that when the arc is formed it is forced across the field and stretched out until it is broken. Another method is to make the arc occur in a confined space so that it will be smothered out. Still another method is to make the cylinder or plates between which the arc jumps of a so-called non-arcing metal, the vapor of which offers a high resistance to the discharge. Some arresters will work on either direct or alternating current; but, generally speaking, the arrester has to be selected with reference to the voltage of the circuit on which it is to be used and also with reference to the kind of current.

53. Ground Connections for Lightning Arresters. Arresters will be of little or no use if good ground connections are not provided for them. The following methods of making ground connections are recommended by the Westinghouse Company: A ground connection for a line or pole lightning arrester is shown in Fig. 48.

Fig. 47

A galvanized-iron pipe is driven well into the ground and the top of it surrounded by coke, which retains moisture; the wire is run down the pole and connected to the top of the pipe as indicated. The wire is sometimes incased in galvanized-iron pipe for about 6 feet from the base of the pole and if this is done, it is well to solder the ground wire to the pipe at *a*. The following method of making the ground connections at the station is recommended: A hole 6 feet square is dug 5 or 6 feet deep in a location as near the arresters as possible,

preferably directly under them. The bottom of this hole is then covered with charcoal or coke (crushed to about pea size) to a depth of about 2 feet. On top of this is laid a tinned, copper sheet, about 5 feet by 5 feet, with the ground wire (about No. 0 B. & S.) soldered completely across it. The plate is then covered with a 2-foot layer of coke or charcoal and the remainder of the hole filled with earth, running water being used to settle it. This will give a good ground, if made in good, rich soil; it will not give a good ground in rock, sand, or gravel. Sometimes grounds are made by putting the ground plate in a running stream. This, however, does not give as good a ground as is commonly supposed, because running water is not a particularly good conductor and the beds of streams very often consist of rock. When lightning arresters are installed, all wires leading to and from them should be as straight as possible. Bends act more or less like a choke coil and tend to keep the discharge from passing off by way of the arrester.

Fig. 48

ARRESTERS FOR DIRECT CURRENT

54. Garton Arrester.—Fig. 49 illustrates **the Garton arrester.** The discharge points are of carbon, shown at *h* and *j*. These are about $\frac{1}{32}$ inch apart, and the lower one is connected to ground; *f* is a coil of wire wound on the tube *g*,

closed at the top; *e* is a small core of iron attached to the rod *d*, which in turn connects, by means of a small flexible cable, to one end of a resistance *b*. The other end of the coil connects to the other end of the resistance, to which the line also connects. The resistance *b* is made up of a stick of graphite, which, having practically no inductance, offers little or no opposition to the discharge and is used to limit the rush of current that follows the discharge. The discharge comes in over the line to *a*, passes through *b* to the rod *d*, thence to the carbon point *h*, and jumps the air gap to the ground. The discharge is followed by current from the dynamo, and, since the coil is in shunt with the resistance, part of the current will flow through the coil, thus drawing up the core *e* and breaking the arc between *e* and *h*. The fact that the arc also takes place in the enclosed tube tends to put it out. As soon as the discharge has passed, the core drops back and the arrester is ready for the next discharge. This arrester can be used on either direct- or alternating-current circuits.

FIG. 49

55. Westinghouse Arrester.—Fig. 50 shows a **Westinghouse arrester** used on direct-current circuits. It has no movable parts, and the arc is extinguished by smothering it in a confined space. Two terminals *b*, *b* are mounted on a lignum-vitæ block and are separated by a space somewhat less than $\frac{1}{8}$ inch. This space is crossed by a number of charred grooves, so that although the resistance in ohms between the terminals is very high, the lightning will readily leap across the space. The block *A* is covered by a second block, not shown in the figure, that excludes the air and confines the arc to the small space between the terminals.

When the arc tends to follow the discharge, the small space is soon filled with a metallic vapor that will not support combustion. It should be noted that this arrester is intended for use on direct-current circuits only, where the pressure does not exceed 600 or 700 volts.

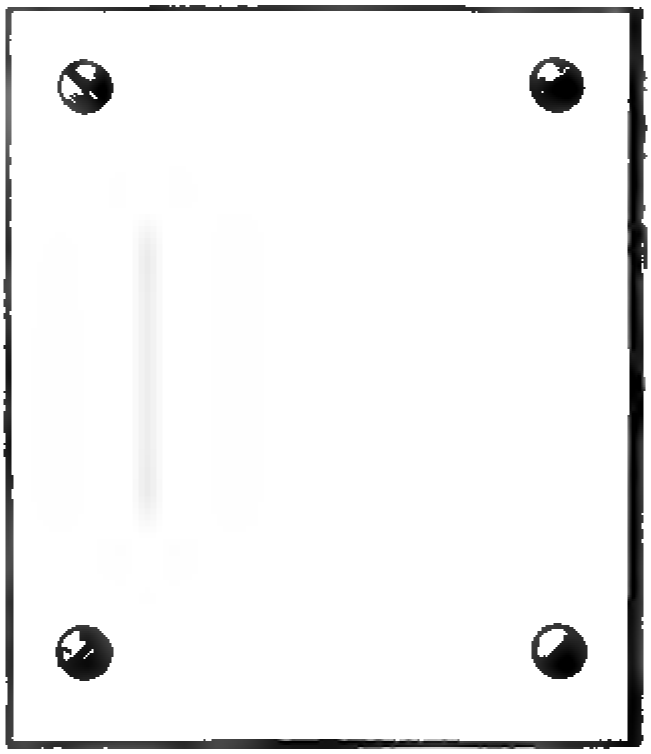


FIG. 50

56. General Electric Arrester.—In the **General Electric arresters** for direct current, the arc is blown out by making it occur in a magnetic field provided by an electromagnet. Fig. 51 shows a direct-current arrester with the cover removed; the case and cover are made of porcelain. The

(a) FIG. 51 (b)

part (*b*) holds the blow-out coil *c* with its polar projections *h*, *h*;

r is a graphite resistance for limiting the current. The electrodes are mounted in the cover and are held by clips *k*, *k'*; the air gap *a* is about .025 inch in length. When the cover is in place, clips *k'*, *k'* make contact with the tongues *k*, *k*, and give the scheme of connections shown in Fig. 52. Here *a* represents the air gap, shown also at *a*, Fig. 51 (*a*), *x y* is the blow-out coil, *r r'* the graphite resistance. The ground connection is made to the lower end *l* of the resistance, and the line is connected to the upper electrode. The terminals of the blow-out coil

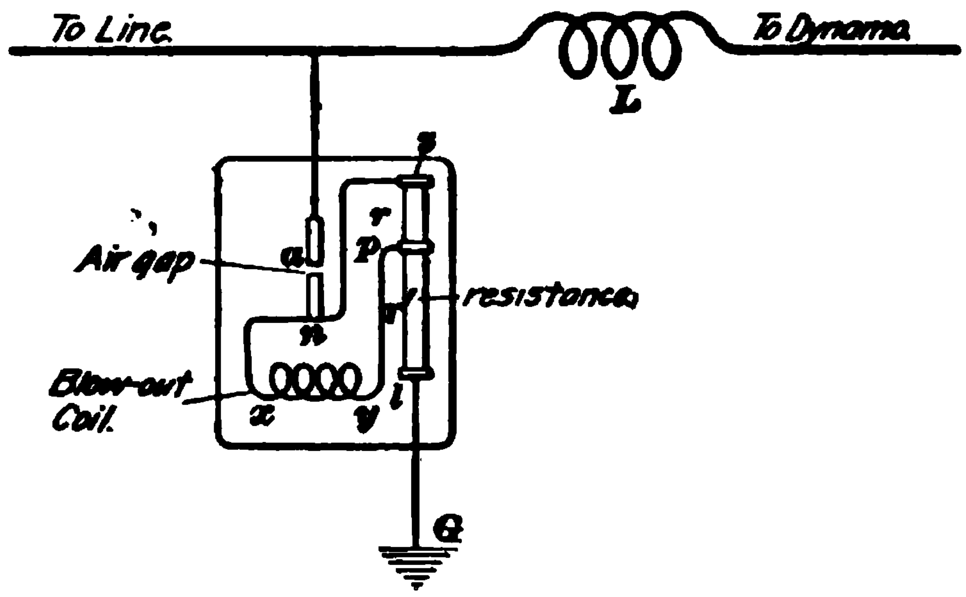


FIG. 52

connect to *z* and *p*, so that the coil is in parallel with a portion of the resistance. When a discharge comes in over the line, it jumps the air gap and passes to the ground through the resistance, and when the current follows the discharge, part of it passes through the blow-out coil. When the cover is placed in position, the air gap *a* falls between the pole pieces *h*, *h*, and the arc is blown out through an opening in the cover. A portion of the resistance *r'* is in series with the coil and spark gap, and thus limits the amount of current that tends to follow the discharge. The ordinary type of this arrester is suitable for any direct-current circuit using pressures of 850 volts or less.

ARRESTERS FOR ALTERNATING CURRENT

57. Westinghouse Arrester for Alternating Current.—Fig. 53 shows a type of arrester that has been largely used by the Westinghouse Company on alternating-current

circuits. It is known as the Wurts non-arcing arrester, and consists of a number of milled cylinders *a*, *a* separated from each other by small air gaps. The end cylinders are connected to the lines and the middle cylinder to the ground. With this arrangement, a single arrester does for both sides of the line; where, however, the line pressure is high, a separate arrester is used for each side; and for very high pressures, such as are used on long-distance lines, a number of arresters are connected in series. When a discharge comes in over the line, it jumps the gaps between the

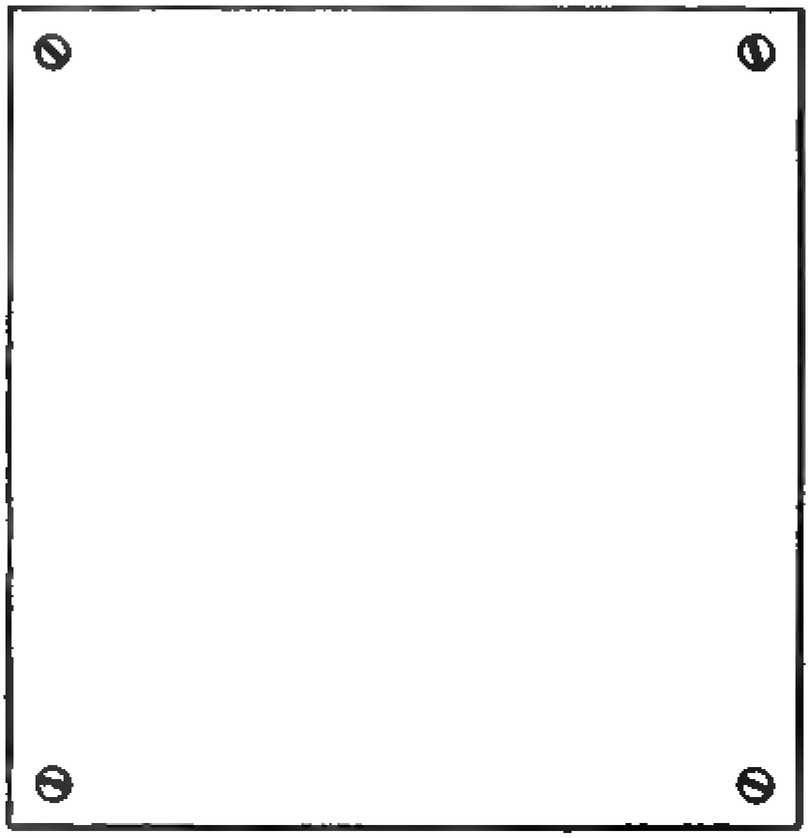


FIG. 58

cylinders and passes to the ground. It is claimed that the arc does not hold over, because the gases formed by the volatilization of the metal will not support an arc. The cylinders are made of what is known as non-arcing metal. Others claim that the suppression of the arc is due to the cooling effect of the cylinders and the alternating nature of the current. These arresters should be examined from time to time and the cylinders rotated slightly so that they will present fresh surfaces to each other.

58. General Electric Arrester for Alternating Current.—Fig. 54 shows an arrester used by the General Electric Company for alternating-current circuits. It is somewhat similar to the Wurts arrester, except that fewer spark gaps are used and a non-inductive resistance *r* is inserted in the circuit in order to limit the current following the discharge. The spark gaps *a*, *a* are between the heavy metal cylinders *b*, *b*, *b*, the middle one of which is connected to ground in the double-pole arrester shown. This arrester, like the previous one, is not suitable for use on direct-current circuits.

The arresters just described have been shown as arranged for indoor use in the station. They may, however, be used on the line, in which case they should be mounted in a weather-proof box made of iron or wood. The connections to and from the arresters should be made with wire not less than No. 4 B. & S.

FIG. 54

59. Westinghouse Arrester for High-Tension Lines.—When lightning arresters are used on high-tension lines, they usually consist of a number of air gaps connected in series between the line and the ground, the total length of air gap being so proportioned that the normal voltage of the system, even if one line becomes grounded, will not cause a current to jump across the gaps; the gaps are generally used in connection with a resistance that will prevent a rush of current after a discharge. A choke coil is also used to choke back the electrostatic wave passing along the line, and make it take the path to ground. Fig. 55 shows one of the air-gap units used with Westinghouse high-tension lightning arresters. It consists of seven knurled cylinders *a*, *a*, separated by six $\frac{1}{32}$-inch air gaps, and made of non-arcing metal.

The cylinders are arranged so that they can be revolved in the porcelain holders *b*, *b* in case the parts facing each other should be burned by the discharge.

Fig. 56 shows the connections of a **Westinghouse low-equivalent arrester** as arranged for a 6,000-volt circuit. The line to be protected is connected at point *A*. Two sets of gaps *B* and *C* are connected in series and to the ground through a series-resistance *R'*. The gaps *C* are shunted by a resistance *R* and are known as *shunted gaps;* gaps *B* are called *series-gaps*. When the potential at *A* rises to an abnormal amount due

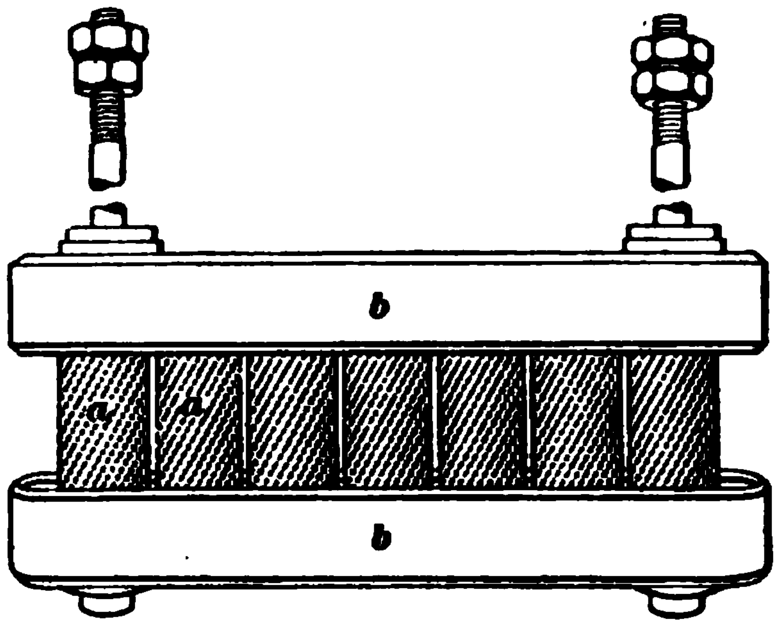


FIG. 55

to a lightning discharge or other cause, a discharge leaps across the series-gaps *B*. If the discharge is heavy, it will meet with a large amount of opposition in the resistance *R*, and will pass over gaps *C* and resistance *R'* to ground. The current that tends to follow the discharge and that is maintained by the dynamo will take the path

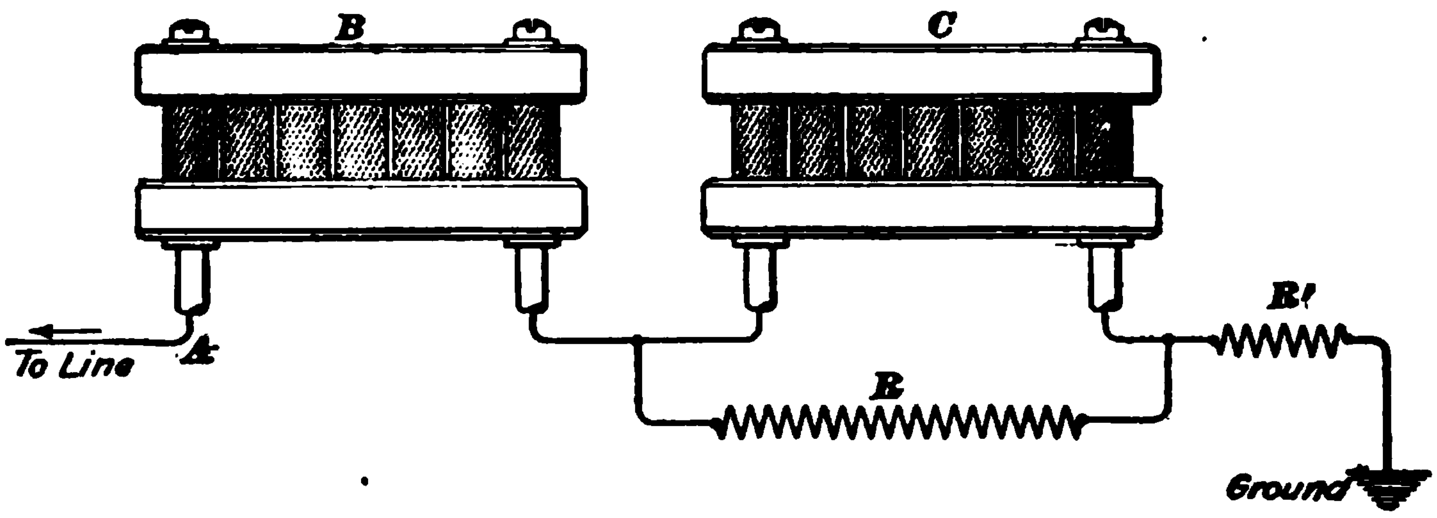


FIG. 56

through *R* instead of passing across gaps *C*, so that the effect of the shunted resistance is to withdraw the arc from gaps *C* and at the same time cut down the volume of current so that the series-gaps can suppress the arc. By using this arrangement a smaller number of gaps at *B* is needed than

would otherwise be necessary. The series-resistance R' is used to limit the initial flow of current and prevent burning of the cylinders B.

Fig. 57 shows the arrangement of one of these arresters with its choke coil. The spark gaps are at a, a, while the

To Line.

To Apparatus.

FIG. 57

resistances are mounted in suitable holders b, b. The arrester shown in Fig. 57 is for 8,500 volts. For arresters of higher voltage than this, the series-resistance is not mounted on the same panel with the other parts, but is placed separately on suitable columns that provide thorough insulation.

60. In the selection of lightning arresters the following points should be kept in mind:

1. The width and number of spark gaps should not be so great as to require the potential of the lightning charge to

be as high or higher than the potential necessary to rupture the insulation of the system.

2. On account of its nature, a lightning arrester is evidently exposed to severe potential strains; consequently, all live parts must be well insulated. On arresters for low voltages it is not a difficult matter to secure proper insulation, as the construction of the arrester itself affords protection. On high-tension arresters, however, proper insulation is a more difficult matter.

3. The general design and construction of the arresters, together with the necessary adjuncts, should be such as to withstand very heavy lightning discharges without destruction.

4. As current is apt to follow the slightest discharge, it is necessary that the arrester should be designed to break the arc quickly without permitting an excessive flow of current.

5. Line terminals should not be exposed in arresters in such a manner as to permit of the accumulation of dust, dirt, bugs, cobwebs, etc., which may facilitate the formation of short circuits and resulting arcs across terminals.

6. Arresters should be designed to handle heavy discharges of atmospheric electricity without permitting the same to follow the circuit and puncture the insulation of the station apparatus.

61. The importance of adequate protection becomes greater with the increased extension of the system, for the reason that the larger systems encounter different atmospheric conditions by extending over greater areas, and the possibility of trouble increases, also the amount of possible damage resulting from breakdowns. Thunder storms that may occur miles distant might be unknown at the station except for the snapping of the arresters or some sudden discharge.

The object should be to select the best method of protecting the system and then to apply a sufficient number of lightning arresters judiciously located in suitable positions on the system to prevent absolutely any disruptive discharges from entering the station and damaging the apparatus.

Special sets of arresters should be connected immediately outside of the station. On account of the extreme suddenness of the surges caused in the line by lightning discharges and other static disturbances, the gaps of the arrester, and ground connection also, must be able to discharge electricity very freely, in fact more rapidly than it appears on the line; otherwise, a dangerous rise of potential on the line will not be prevented.

INSTALLATION OF ARRESTERS

62. Before arresters are installed, the characteristics of the surrounding territory should be carefully studied, and if possible, statistics obtained regarding the frequency and severity of atmospheric electrical disturbances. The information obtained may be somewhat of a guide as to the amount of protection necessary.

63. Location of Arresters.—As regards the location of lightning arresters, electric systems may be divided into two groups:

1. Systems in which the individual pieces of apparatus, such as transformers, motors, arc lights, etc., are many in number and widely scattered. In these cases lightning arresters should be located at a number of points for the purpose of protecting the whole line; they should be more numerous on the parts of the line particularly exposed, and fewer in number on the parts that are naturally protected, especially those parts shielded by tall buildings or numerous trees. Special efforts should be made to protect the station by connecting sets of arresters on each line and causing the discharge to pass to ground before it enters the station. No definite statement can be made as to the number of arresters needed per mile, as the requirements will vary widely according to atmospheric disturbances in the locality.

2. Systems in which the apparatus is located at a few definite points, as on a high-tension transmission line. In such cases the arresters should, in general, be located to protect especially those points where apparatus is situated;

that is, should be placed with the object of protecting the apparatus rather than the line as a whole. Where circuits are part underground and part overhead, sets of arresters should be connected at the points of entrance to and exit from the underground system.

When determining the safest method of mounting and insulating the arresters, it should be estimated that all parts of the arrester except the grounded end of the series-resistance may be momentarily at line potential during the discharge; therefore, the necessity of extra insulation becomes self-evident.

Two high-tension arresters attached to different line wires should not be placed side by side without either a barrier or a considerable space between them. It is preferable to place them on different poles.

PROTECTION BY CONTINUOUS DISCHARGE

64. For overhead systems, excellent protection has been secured by the placing of barbed wires on the pole lines above the lines used for distribution; the barbed points serve to collect the electricity, and the barbed wires should be thoroughly grounded, at least as frequently as every three or four poles. An easy method of doing this is to put a copper plate under the base of the pole, having the ground-wire connection soldered on the plate and stapled along the surface from the base of the pole to the top, where it is connected to the barbed wire. The effect of this sort of protection is to discharge the atmospheric electricity silently and continuously, and this method under severe test has proved successful over large areas, with systems reaching from 30 to 50 miles or more from the station.

Fig. 58 shows the principle of the **Westinghouse tank arrester,** a type that has been much used on street-railway circuits where one side of the system is grounded. The arrester is connected to the series of choke coils S by closing plug switches K, K, K. The arrester consists of tanks T, T, T containing carbon electrodes c, c, c; the line is attached at L

and the other end of the choke coil goes to the dynamo or line bus-bar. A circulation of running water is maintained through the tanks and there is thus a continuous non-inductive path of high resistance to ground for any charges that may accumulate on the line. The water has such a high

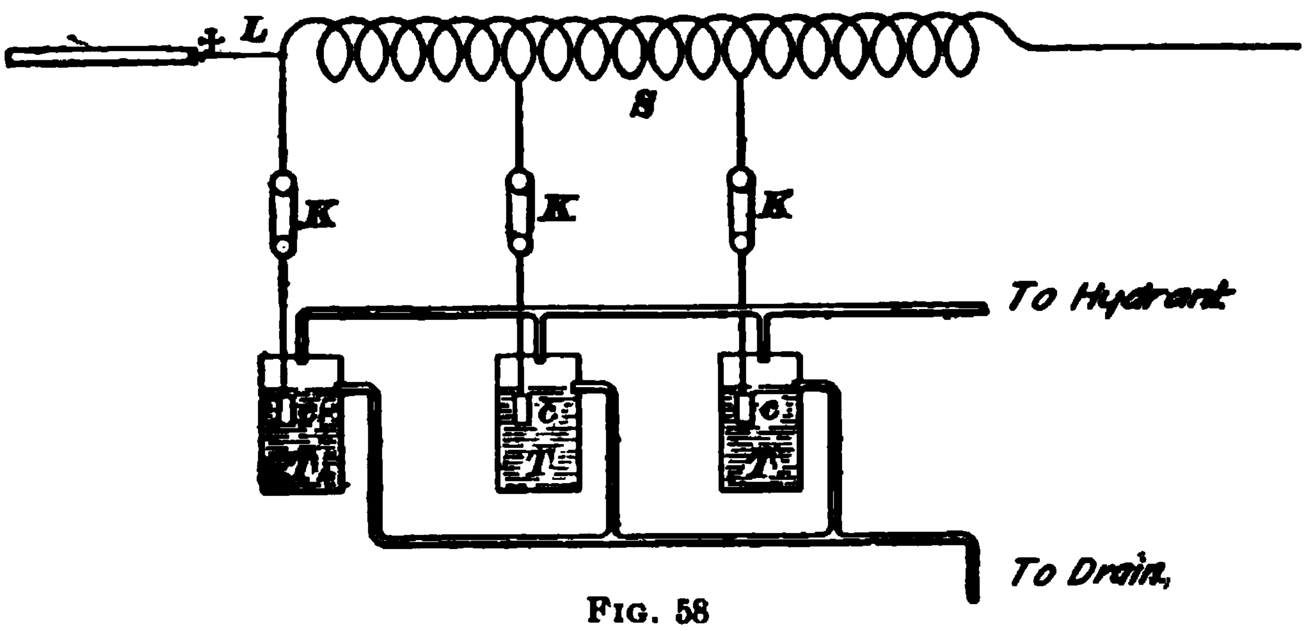


FIG. 58

resistance that the leakage of dynamo current to ground is not large. There is some leakage, however, and this type of arrester is only connected to the system during thunder storms, but while connected it affords very efficient protection.

PROTECTION FROM STATIC CHARGES

65. Static Effects on High-Tension Systems.—It has been found on systems where high pressure is used that under certain circumstances, parts of the system may be subjected to pressures very much higher than the normal. These effects, for want of a better name, are spoken of as being due to "static." They may be caused by any sudden change in the E. M. F. of the system, as, for example, when a dead circuit is suddenly connected to live bus-bars, when a transformer is switched on to a circuit, when a circuit is suddenly cut off from the bus-bars, etc. These effects are not due so much to the static charges themselves, but to the fact that when a device is switched on to a live circuit, a current wave at once tends to pass through the device, and if this wave meets with opposition, pressures much higher than the ordinary pressure of the system may be set up. This is somewhat analogous to the case where a current of

water is flowing rapidly through a pipe. There will be a certain pressure on the walls of the pipe due to the head of water, and this pressure will be practically constant. If, however, the flow of water be stopped by suddenly closing a valve in the pipe, the pressure will for an instant rise to a very high amount, producing the well-known water-hammer effect. These sudden rises in pressure on high-tension circuits may result in puncturing the insulation of transformer coils, armature coils, cable insulation, or other parts exposed to the high pressure. Take the case where a transformer is suddenly connected to a source of high E. M. F. The windings tend to become charged instantly, but owing to the self-induction of the coil the current wave that tends to enter is choked back and a pressure may be set up between the various layers of the winding that is very much higher than the normal, thus tending to cause a breakdown. To overcome these bad effects, a choke coil may be inserted in series with the device to be protected. This coil chokes back or flattens out the wave, and allows the pressure applied to the device to rise gradually. The choke coil must be heavily insulated, and large enough to flatten out the wave so that the latter will not injuriously affect the device to be protected. This means that the coil must be large, and it is difficult to insert a large choke coil in the circuit without causing a considerable waste of energy and drop in voltage. Another method of protection is to use a choke coil in combination with a spark gap that will break down whenever the pressure rises above a predetermined amount. This arrangement is practically the same as a lightning arrester, and a number of large plants have their lines fully equipped with lightning arresters even though the distributing lines are entirely underground and hence safe from lightning discharges. The lightning arresters are in such cases installed to protect the cables against abnormal pressures caused by the so-called static effects.

66. Static Interrupter.—In some cases, especially on high-tension lines operating at pressures higher than 16,000

or 18,000 volts, a device known as a **static interrupter** is installed to protect large transformers and other apparatus from the high pressures mentioned above. Fig. 59 shows the essential parts of the device as made by the Westinghouse Company; one line only is shown in the figure, but it is necessary, of course, to place one of the interrupters in each line. A is a choke coil and B the primary coil of a transformer or the winding of other apparatus to be protected; C is a condenser connected between A and B; the other terminal of C is connected to ground through a fuse D. If the primary coil B were suddenly switched on to a live line without the interposition of A or C, a very high potential would at once be developed at point E, because the current wave could not penetrate the layers of the winding instantly. The coil A retards the wave, and furthermore the condenser C, having a large capacity compared with the coil B, takes up a considerable portion of the charge, thus reducing the potential of E for the time being and allowing the charge to progress well through the coil before the pressure at E rises to the full amount. In other words, the condenser C acts in much the same manner as an air chamber used on a water pipe to prevent the shock due to a water hammer. By using the condenser in conjunction with the choke coil, a much smaller coil is sufficient than if the coil were used alone, and it can thus be designed so that it will not insert an objectionable amount of resistance or inductance in the circuit. In practice, the coil A and condenser C are mounted together in a case filled with oil, so that the interrupter has about the same appearance as an ordinary oil-insulated transformer. The interrupters are connected directly to the apparatus to be protected so as to practically form part of the apparatus, because they must be so situated

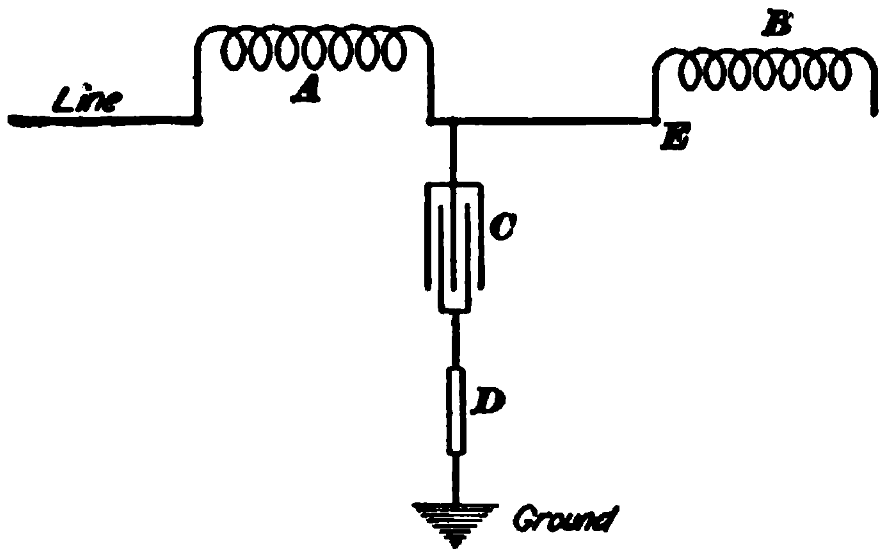


FIG. 59

that they will come between the device to be protected and the source of static disturbance, as, for example, a high-tension switch.

Overhead systems will naturally be equipped with lightning arresters and these will serve to a considerable extent as protection against static discharges. Underground systems carrying current at high potential are liable to accumulation of static charges that may cause a rupture of the cable insulation. Assuming that alternating current of high potential is transmitted through an underground system, it will be found that there is a static charge developed in the cable covering or, under some conditions, in the conduit ducts. Certain types of conduit have been found to develop condenser capacity under these conditions. A 6-foot section of 3-inch, creosoted, pump-log conduit was tested for capacity with an insulated wire drawn through it and connected in circuit with a high-potential current. In the darkness, a faint blue light could be distinguished on the interior surface of the duct. When circuits are quickly opened, the cable tends to set up violent oscillations of the system, and the resultant static potential is liable to rupture, at its weakest point, the insulation of the cable. Static charges are also liable to accumulate on generators and switchboard apparatus. Electrostatic ground detectors should be used to show the appearance of any static charge on the line, and on which particular conductor it may be located.

FIELD RHEOSTATS

67. Field rheostats are inserted in the field circuits of the generators in order that the voltage may be adjusted by varying the field strength. The rheostat must therefore be able to carry the field current continuously without overheating. The resistance of the rheostat will depend on the resistance of the field winding with which it is used, and the range of voltage variation desired. Very often the rheostat has a maximum resistance about equal to that of the field, though in many cases it is not necessary to have as much as

this. Field rheostats are made in a great variety of styles and sizes suited to various classes of machines. They are also constructed for various methods of mounting, but all consist of a suitable resistance connected to a multipoint switch of some kind so that the amount of resistance in the field circuit can be varied. Small or medium-sized rheostats are generally mounted on the rear of the switchboard and operated from the front by a hand wheel. For large rheostats the resistance can be separate from the board with leads

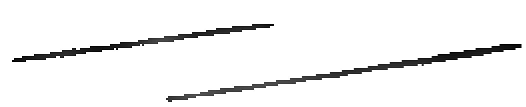


Fig. 60

running to the switch located on the back of the board, or the switch can be mounted with the resistance and be operated from the switchboard by means of chain and sprocket wheels, or from a pedestal, with a hand wheel, placed in front of the board. Either of the latter methods are preferable to running leads from the resistance to the board, because quite a number of wires are required and there is danger of some becoming broken. In very large stations, the rheostats are

often bulky and must be placed quite a distance from the switchboard; in such cases the rheostat switch is moved by means of a small motor controlled from the switchboard.

68. Fig. 60 shows a **General Electric field rheostat** of a type much used for 500-volt railway switchboards. The rheostat is mounted on the back of the board and operated by the hand wheel *W* in front. The resistance wire or strip is wound on asbestos tubes that are afterwards flattened and clamped between pieces of sheet iron covered with asbestos, the iron strips serving to conduct the heat from the wire. In rheostats of large capacity, the resistance is in the form of cast grids. Fig. 61 shows the connections for the rheostat, Fig. 60. A small resistance *c* is connected to the contact rings *b*, *b* and contacts *a*, *a'*. When the arm is in a position where *a*, *a'* are on adjacent contact points, resistance *c*, which is equal in amount to the resistance between the rheostat contacts, is in parallel with the resistance between the contacts. Thus, by using resistance *c*, the change in resistance due to a movement of the arm from contact to contact is one-half what it would be if no auxiliary resistance were used. The variations in field strength are, therefore, as gradual as in an ordinary rheostat using twice the number of contacts.

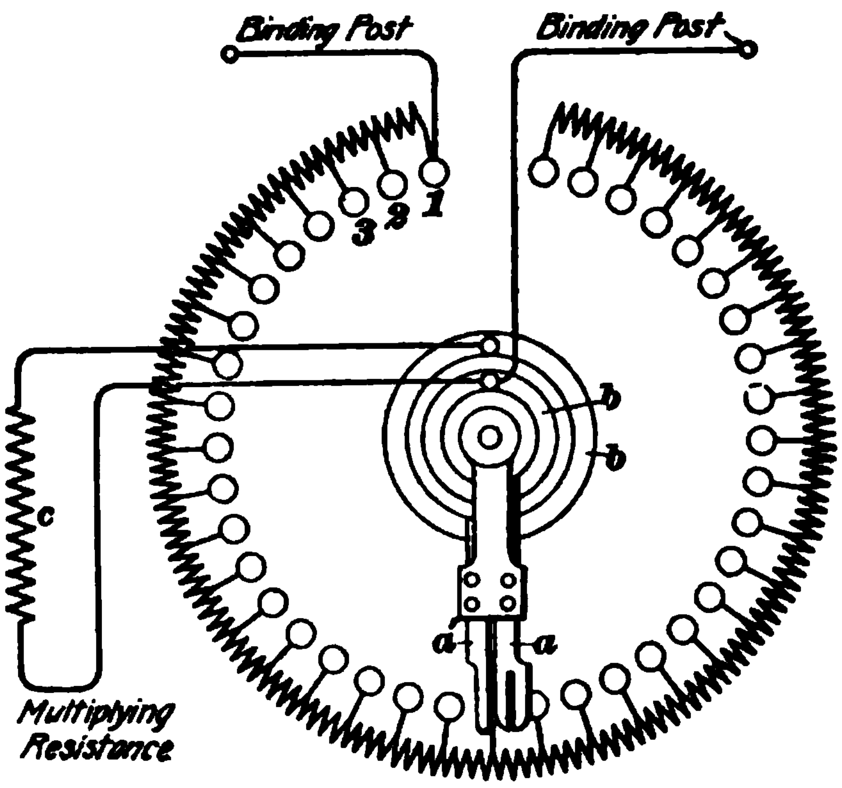


FIG. 61

69. Field Switches.—Field switches are used to open the field circuits of dynamos and they are, therefore, of comparatively small current-carrying capacity. Field windings, particularly those of large alternators or high-voltage, direct-current machines, have a high inductance, and if the circuit is suddenly opened very high E. M. F.'s may be induced,

sufficient in many cases to break down the field insulation. It is therefore necessary, with such machines, to arrange the field switch so that when the field circuit is broken, a path is at the same time established through a discharge resistance. This allows the induced E. M. F. to set up a current through the local circuit thus provided, and strain on the windings is avoided. Fig. 62 shows a common arrangement of field switch and discharge resistance as used for 500-volt street-railway generators. The tongue *t* is wide enough to bridge over the gap between the contact segments *a*, *a'* of the switch *S*, which is shown in the position that it occupies when the generator is in operation. The current then passes through the field rheostat *r* and the switch *S*, as indicated by the arrowheads. When the switch is moved to the position indicated by the dotted line, connection between the field and the negative side of the armature is broken, but before the break takes place, tongue *t* comes into contact with *a'*, so that the shunt field, the rheostat *r*, discharge resistance *r'*, and pilot lamp *l* all form a closed circuit. The shunt field is thus able to discharge through this closed circuit. When the machine is being started, the tongue *t* is placed in its mid-position, so that current can flow through *r'* and *l* as well as through the shunt field and rheostat *r*. As the machine builds up, the pilot lamp becomes brighter, thus giving the attendant an indication as to whether the machine is "picking up" properly or not. After the machine has come up to voltage, the switch is moved to the position shown in the figure and the pilot lamp is cut out. On some boards, five or six lamps in series are used in place of the resistance *r'* and the single lamp *l*. Another type of field

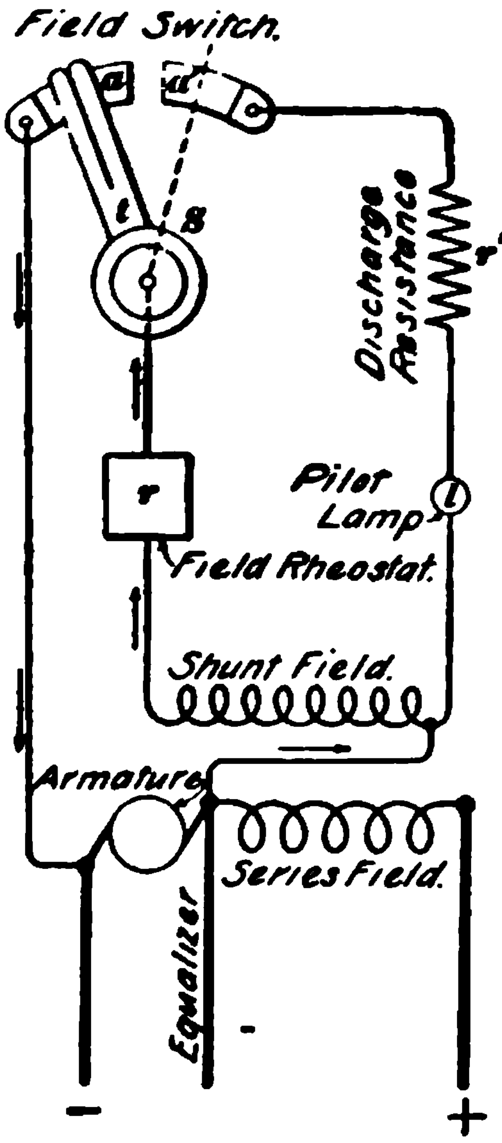


Fig. 62

switch with field-discharge resistance, as used in the exciting circuit of alternators, is shown in Fig. 73.

70. Recording Wattmeters.—Well-equipped switchboards are generally provided with one or more **recording wattmeters**, to record the output, in kilowatt-hours, of each machine or of the station as a whole. Readings of the total output are very valuable in making tests on the efficiency of the station and in keeping track of the cost per

FIG. 63

kilowatt-hour. Sometimes it may be desirable to know the output of individual machines, but usually a knowledge of the total output is sufficient and a single total output recording meter is installed, as shown at *11*, Fig. 65.

Fig. 63 shows a **Thomson recording wattmeter** for use on direct-current switchboards. These meters have to carry large currents, hence their construction differs somewhat from the ordinary Thomson meter, though the principle

of operation is the same. The series-coils of the ordinary meter are here replaced by the heavy copper bar *a*, through which the current passes, connection being made on the back of the board to the lugs *b*, *b*. Above and below this bar are the two small armatures *c*, *c*, which are connected, in series with a resistance, across the line, so that the current in them is proportional to the voltage. Current is led into the armatures through a small silver commutator *d*, as in the ordinary recording meter, and the reading is registered on a dial *e* in the usual way. The damping magnets used to control the speed are contained in the case *f*. The main current flowing through the crosspiece *a* sets up a field around the crosspiece, and this field acts on the two armatures *c*, *c*. This instrument is constructed so that outside magnetic fields have little or no influence on it. In some of the older styles of meters, the magnetic field surrounding the heavy conductors on the back of the board affected the meter. In this meter any stray field affects both the armatures *c*, *c*, which are so connected that an outside field tends to turn them in opposite directions, and the disturbing effect is thus neutralized. The field set up by the instrument itself is in opposite directions on the upper and lower sides of *a*, so that these two fields propel the armatures in the same direction. For alternating-current boards, total-output recording meters of the induction type are used.

SWITCHBOARDS

71. The **switchboard** is a necessary part of every plant. Its object is to group together at some convenient and accessible point the apparatus for controlling and distributing the current, and the safety devices for properly protecting the lines and machines. Scarcely any two switchboards are alike in every particular; their layout and the type of apparatus used on them depend on the character of the system used, the number and size of dynamos, the number of circuits supplied, etc.

72. General Construction.—Switchboards were formerly made of wood and consisted simply of a built-up board or wall sufficiently large to accommodate the instruments. This construction was objectionable on account of the fire risk, and the only type of wooden board now allowed by the Fire Underwriters consists of a skeleton frame of well-seasoned hardwood filled and varnished to prevent absorption of moisture. A skeleton board of this kind is cheap and is suitable for those places where the expense of a slate or marble board is not warranted. Modern boards are nearly always made of slate, marble, soapstone, or brick tile. Slate is usually satisfactory for low-tension work, but it should be avoided on high-tension boards, because it is liable to contain metallic veins. A good quality of marble is the material generally used for modern boards. The slabs making the boards may vary from ¾ inch to 2 or 2½ inches in thickness, depending on their size. Most central-station slate or marble boards are made 2 inches thick with a bevel around the edge of ½ or ⅜ inch. They are supported by bolting to angle irons *i*, *i*, Fig. 64, and are stood out from the wall by means of braces *b*, *b*. Station boards built up as shown in Fig. 64 are usually about 90 inches high. It has become customary to build up boards in panels, each panel carrying

the apparatus necessary for a generator or one or more feeders. Those carrying the instruments for the generators are known as **generator panels**; those carrying the instruments for the feeders, as **feeder panels**. This system allows the board to be easily extended as the plant grows in size, as panels can be added to those already in use. The extra panels are attached as indicated by the dotted lines in

Fig. 64

Fig. 64, the panels being held together by means of bolts passing through holes *h* in the angle irons. For high-pressure boards using over 3,000 volts, the marble should be polished on both sides in order to secure better insulation. Also, if oil switches are mounted on the back of the board, the marble should be coated with varnish or similar substance to prevent absorption of oil.

DIRECT-CURRENT SWITCHBOARDS

73. Railway Switchboard.—Fig. 65 shows a typical **direct-current switchboard** as arranged for street-railway operation on the ordinary 500-volt rail-return system. The board consists of three generator panels *A*, *A*, *A*, one total-

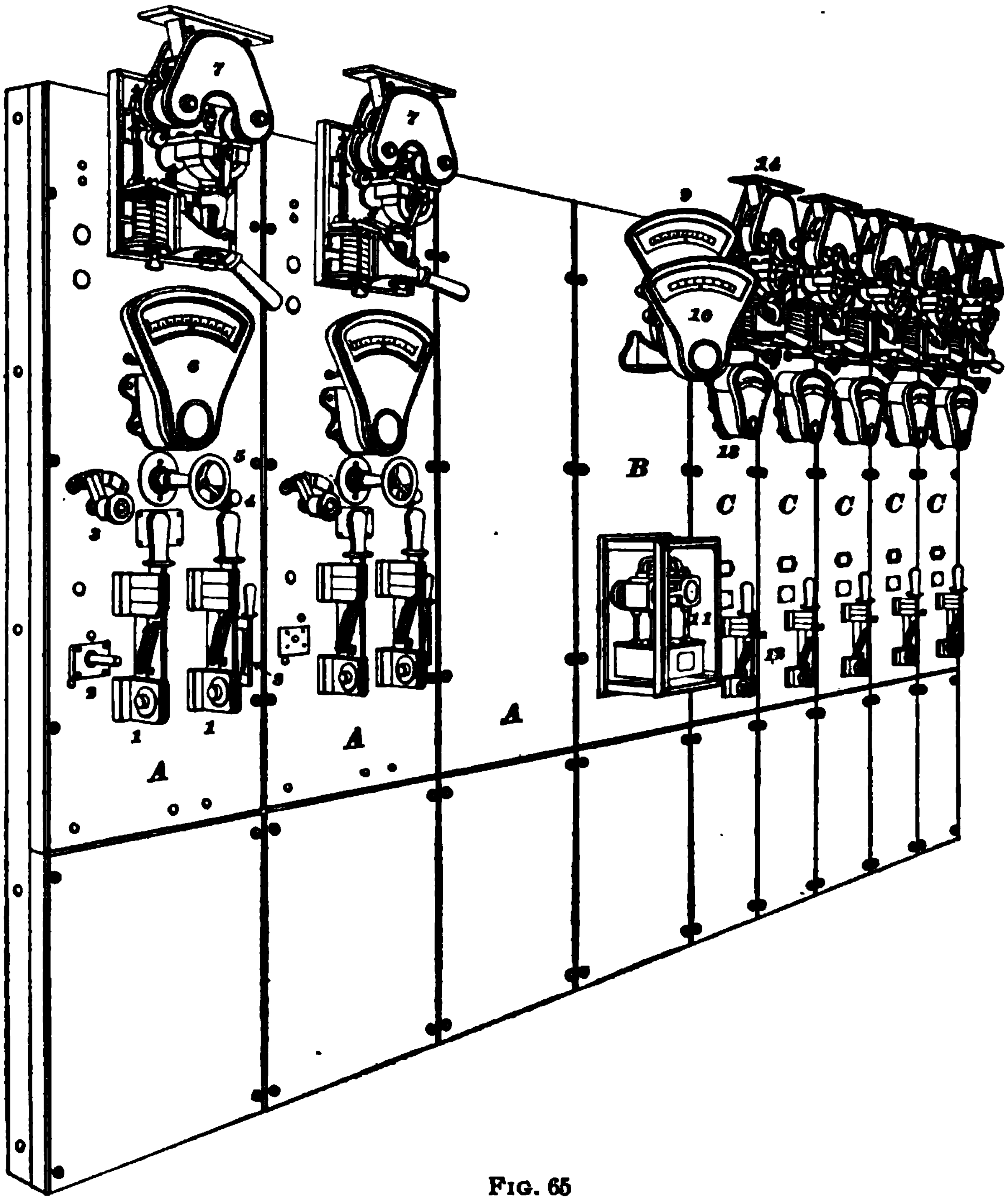


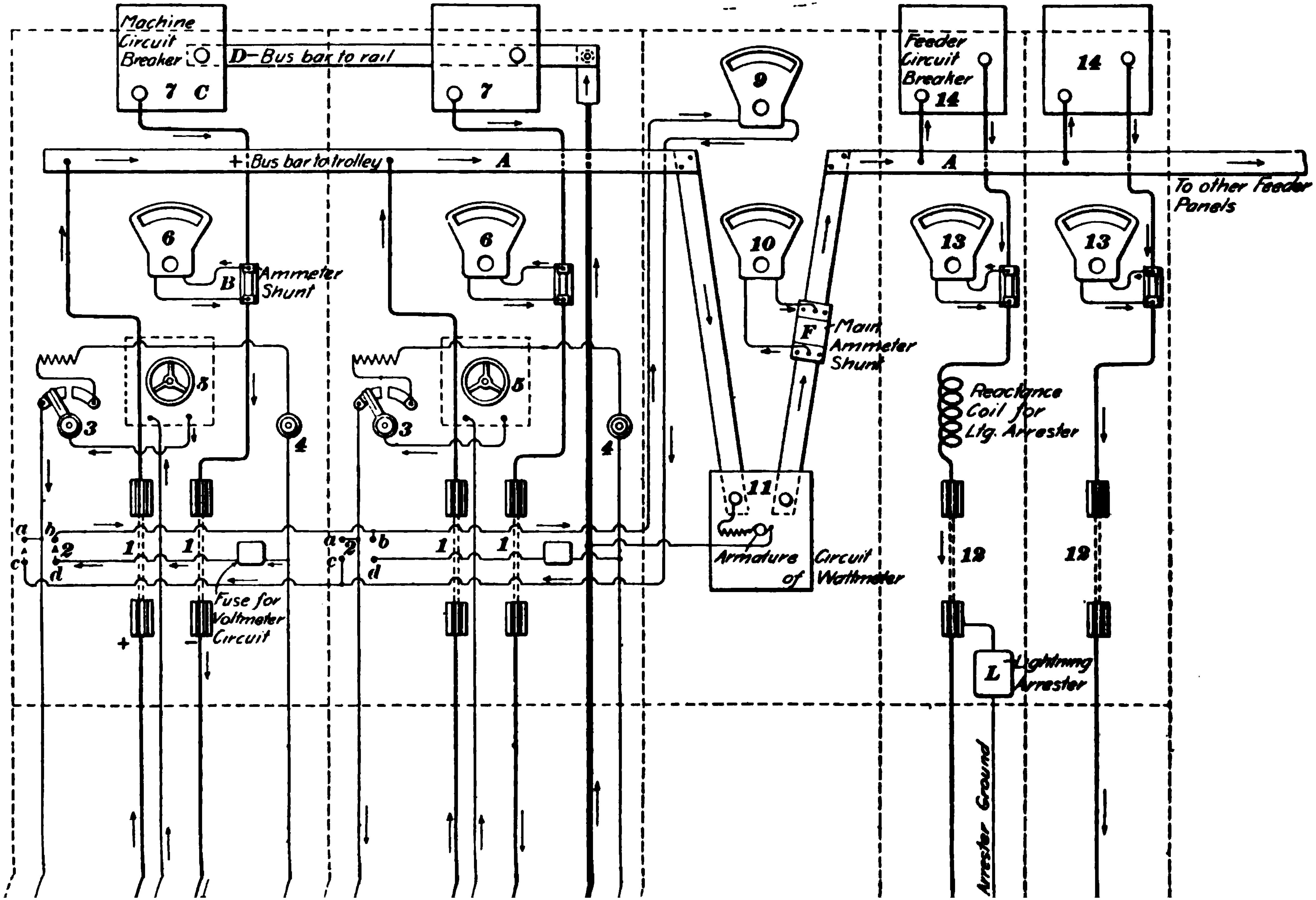
Fig. 65

output panel *B*, and five feeder panels *C*, *C*, etc. One of the generator panels is left blank to provide for a future generator. Each generator panel is equipped with + and − main switches *1*, *1*, voltmeter plug *2*, field switch *3*, pilot-lamp

receptacle *4*, field rheostat (operated by handle *5*), machine ammeter *6*, and machine circuit-breaker *7*. The total-output panel carries a voltmeter *9* that can be connected to either machine by means of the voltmeter plug, a total-output ammeter *10* that indicates the combined current output of the generators; recording wattmeter *11* records the total output in kilowatt-hours. Each feeder panel is equipped with a single-pole feeder switch *12*, a feeder ammeter *13*, and a feeder circuit-breaker *14*. Since on a ground-return railway system the current returns through the rails, which are connected to the negative bus-bar, the feeders are connected to the positive bus-bar only, hence single-pole feeder switches are used.

Fig. 66 shows the connections for the board. Two feeder panels only are shown and the instruments and switches are numbered to correspond with Fig. 65. If lightning-arrester reactance coils are used on the switchboard, they will be inserted as indicated on the left-hand feeder panel. The equalizer switches are mounted on pedestals near the generators and the equalizer connections are not brought to the switchboard. When the voltmeter plug is inserted in either receptacle, terminals *a* and *c*, *b* and *d* are connected, thus placing the voltmeter across either machine; the voltmeter connections are made at the lower terminals of the main switch, or "back" of the switch, so that voltmeter readings can be taken before a machine is thrown in parallel by closing the switch.

74. Lighting or Power Switchboard.—Fig. 67 shows connections for a simple two-wire board suitable for two generators and three two-wire feeders. Three bus-bars are provided, the equalizer bar being mounted on the board. Each generator panel has a machine ammeter *a* connected across ammeter shunt *s*, circuit-breaker *b*, voltmeter plug *c*, main switches *d*, field rheostat *e*, and pilot lamps *h*, *h*. As this board is intended for low pressure, 110 to 250 volts, field switches and field-discharge resistances are not provided. A total-output ammeter *M* is connected between the



Machine Circuit Breaker
7 C
D–Bus bar to rail
7
+ Bus bar to trolley
A
9
Feeder Circuit Breaker
14
To other Feeder Panels
6
B
Ammeter Shunt
10
F
Main Ammeter Shunt
13
5
3
4
Reactance Coil for Ltg. Arrester
11
1
2
a
b
c
d
Armature
Circuit of Wattmeter
12
Fuse for Voltmeter Circuit
+
−
L
Lightning Arrester
Arrester Ground

FIG. 66

§ 25

Dynamo No. 1. Dynamo No. 2.

FIG. 67

generator and feeder panels to indicate the combined current output of the generators; voltmeter *V* indicates the voltage of either machine. Each feeder panel is equipped with a feeder circuit-breaker *g* and feeder switch *f*. The lamps *k*, *l* may be connected either across the bus-bars, as shown for *l*, or to the feeders, as at *k*. In the latter case the lamp will go out when the circuit-breaker of the corresponding feeder trips, and the lamp thus serves as a circuit-breaker telltale. If a lamp ground detector were used on the board, it would be connected as shown by the dotted outline at *D*.

In large stations there are, of course, a large number of generator and feeder panels on the switchboard. This increases the size of the board, but each generator or feeder added merely repeats the connections of the other panels and no new features are involved.

ALTERNATING-CURRENT SWITCHBOARDS

75. The arrangement of ordinary **alternating-current boards** is, in many respects, similar to that of direct-current boards. They are usually built up in panels in the same way as the boards previously described. Owing to the fact that alternators are generally separately excited, the switchboard contains some extra apparatus connected with the exciter that is not found on direct-current boards. The wiring and connections will also depend on whether single-phase or polyphase alternators are used.

76. Single-Phase Generator Panel.—Fig. 68 (*a*) and (*b*) gives front and rear views of a typical alternating-current panel for one single-phase generator. Such a board would be used where only one single-phase machine is operated on a single line, and represents about the simplest possible arrangement. This panel is equipped as follows: Main switch *a*, electrostatic ground detector *b*, voltmeter *c*, ammeter *d*, voltmeter switch *e*, field switch *f*, generator rheostat *g*, exciter rheostat *h*, main fuses *k*, and potential transformer *t*. The main switch *a* is of the quick-break type and is provided with the marble barrier *l* between the blades to prevent arcing

across. The switch *f* is used to disconnect the field of the alternator from the exciter and is provided with auxiliary carbon contacts to prevent burning at the blades. The rheostat *g* is mounted on the back of the board and is operated by a hand wheel in front. This rheostat is connected in series with the field of the alternator, so that the field current may

(a) (b)

Fig. 68

be adjusted. The rheostat *h* is in the shunt field of the exciter and serves to regulate the exciter voltage. Sometimes the rheostat *g* is not used, the field current of the alternator being increased or decreased by raising or lowering the exciter voltage by means of the rheostat *h*. It is best, however, to have the rheostat *g* also, especially if two or more alternators are

excited by the same exciter, because it then allows the field current of each alternator to be adjusted independently of the others. The voltmeter *c* is connected to the machine through the potential transformer *t*, and a small voltmeter switch *e*

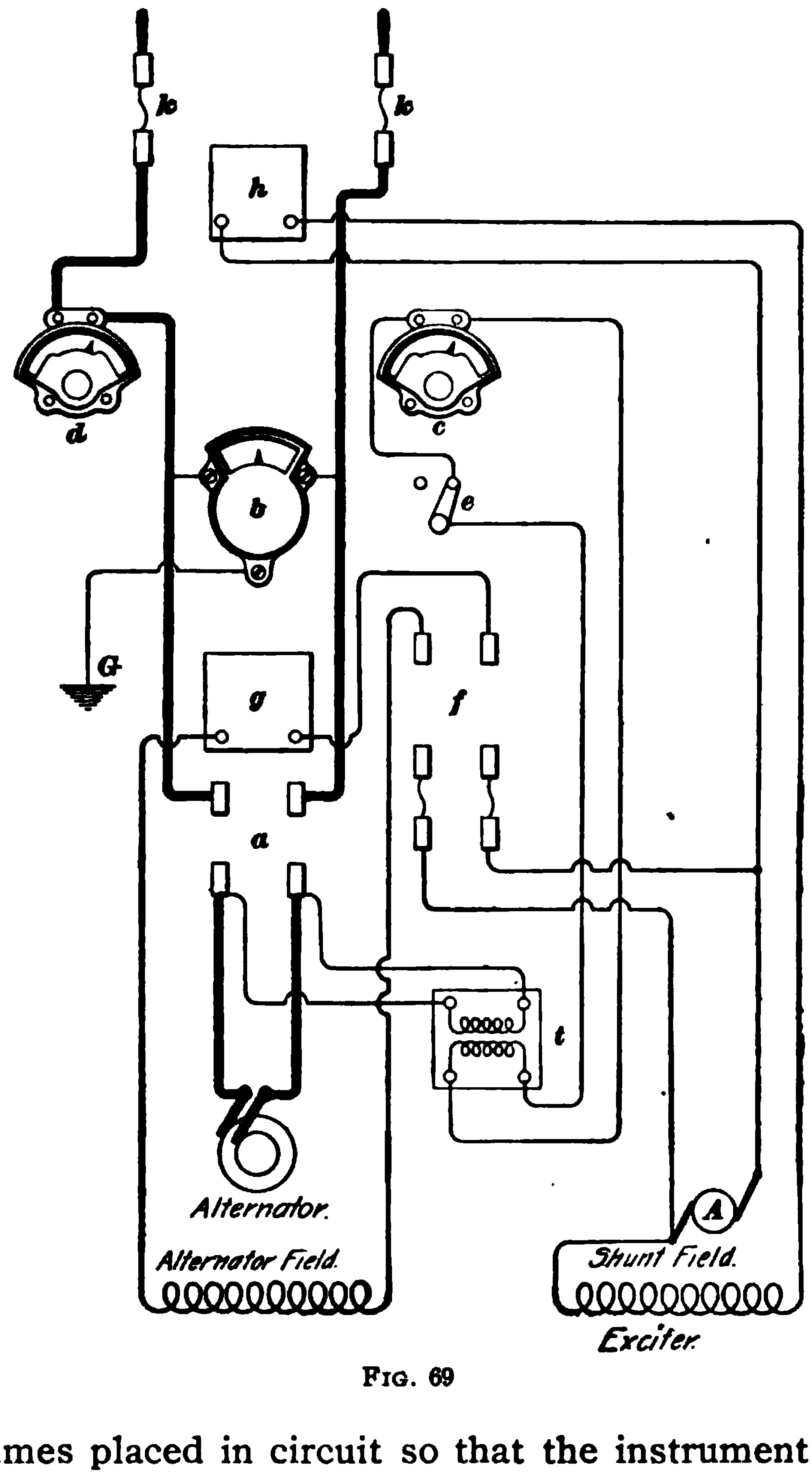


FIG. 69

is somtimes placed in circuit so that the instrument may be cut out of circuit when not needed. The main fuses *k* are of the enclosed type. No synchronizing device is needed on this board, as it is intended for a single machine only.

77. The rear view of the board will give a good idea as to the way in which the wiring is arranged. Heavy rubber-covered wire should be used for this work, and especial care should be taken to see that everything is thoroughly insulated and neatly done. The leads from the alternator connect to terminals *1* and *2*, and the line connects to terminals *3* and *4*. The potential transformer *t* used to lower the pressure for the voltmeter, is mounted on an iron framework at the base of the board, and when the lightning arresters are placed on the board, they are usually mounted on a similar framework rather than on the back of the board itself. This makes them stand out so that they do not crowd the wiring on the back. Fig. 69 shows the general scheme of connections on a board similar to that shown in Fig. 68.

78. Switchboards for Parallel Running.—When alternators are operated in parallel, it is necessary to provide bus-bars and have the different machines arranged so that they may feed into them. Fig. 70 shows connections for two three-phase machines arranged for parallel running, as used by the Westinghouse Company. Main fuses are here provided between the alternator and main switch, and these may or may not be placed on the switchboard itself. The field excitation is carried out in the same way described in connection with Figs. 68 and 69, about the only difference being that field plugs c, c' are used instead of field switches. Three ammeters are provided for each generator, one in each leg of the three-phase system. In many cases, however, two ammeters only are used, as shown on the feeder circuit. T and T' are the potential transformers that furnish current to the voltmeters V, V' and also to the synchronizing lamps l, l'. The voltmeter is also made to serve as a ground detector by using the plug switches R, R' and ground keys k, k'. The synchronizing lamps are connected to the transformers by inserting plugs p, p'.

79. Usually when a number of alternators are operated in parallel, it is advisable to have their exciters arranged so that they may be operated in parallel also. If

one exciter breaks down, the others may then supply the alternator that would ordinarily be supplied by the disabled

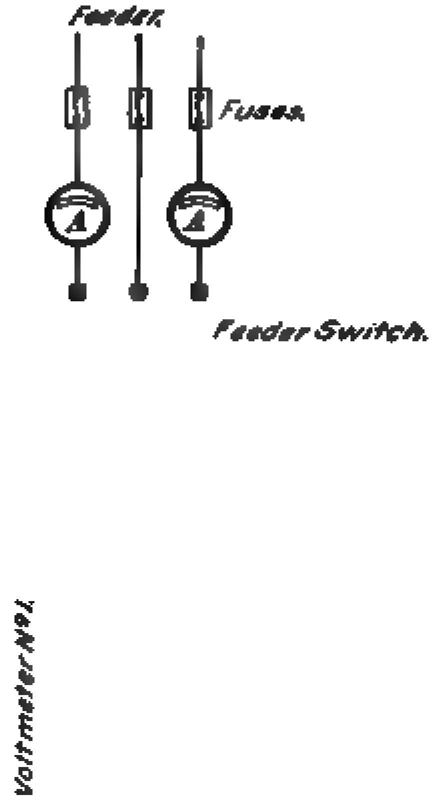


Fig. 70

machine. Again, in large plants, it is quite customary to supply all the alternators with their field current from one

or two large exciters that feed into a pair of exciter bus-bars, from which the several alternators are supplied.

80. General Arrangement of High-Pressure Switchboards.—In low-pressure work, the switchboard consists of a group of slate or marble panels on which the switches, bus-bars, instruments, and all devices necessary for the control of the station output are placed. Such crowding of the parts is dangerous on a high-pressure board, and the tendency in large stations is to separate the high-pressure switches and bus-bars so that a short circuit on one part will not spread to others and result in a serious interruption of the service. The switchboard panels in this case carry only the instruments and small switches necessary for controlling the main switches that are usually operated either by compressed air, electric motors, or electromagnets. No parts carrying high pressure are exposed on the surface of the board, thus insuring safety to the attendant; a switchboard arranged on this plan occupies a large amount of space. Fig. 71 shows a cross-section of the switchboard in the Waterside station of the New York Edison Company. This board controls the output of 16 generators, each having a capacity of 4,500 kilowatts at 6,600 volts. The board is a good example of a number that have been installed in modern stations delivering a large output at high pressure, and brings out the method of separating the various parts. The main cables from the generator first pass through the generator oil switch *A*, and from there they lead to the two selector oil switches *B*. The object of these switches is to allow the generator to be connected to either of the sets of bus-bars *C*, *D*. There are, therefore, two oil switches in series between any generator and the bus-bars into which it is feeding, so that if one switch fails to operate at any time, the generator can be cut off by means of the other. From the bus-bars, the current passes to a non-automatic oil switch *E*, and then through an automatic oil switch *F*, from whence it passes out on the feeder *G*. E' and F' are a similar pair of switches for another feeder. *H*, H' are knife-blade switches that allow

Fig. 71

Fig. 71

any feeder to be connected to either pair of bus-bars. These switches are never opened while the current is on; other knife-blade switches *K*, *K'* allow switches *B* to be disconnected from the bus-bars. The potential transformers used for supplying current to the voltmeter, wattmeters, or other instruments are shown at *L*, and the current transformers are shown at *M*. It will be noted that all the transformers, bus-bars, knife switches, and working parts of the oil switches are separated from each other by brick partitions, and the various parts are so widely separated that there is little danger of fire communicating from one to the other.

The instruments connected with the control of the feeders are mounted in the upper gallery at *N*, there being a panel for each feeder. On these panels are mounted the feeder ammeters, indicating wattmeter, power factor indicator, pilot switches for controlling the feeder oil switches, and all other devices connected with the control and measurement of the outgoing current.

81. The apparatus for the control of each generator is mounted on a pedestal at *O*, there being a pedestal for each generator. This pedestal has mounted on it the rheostat dial switch for adjusting the field excitation of the alternator, the resistance controlled by this switch being mounted at *P* in the gallery below. In addition to this, each pedestal is provided with a field switch for cutting off the exciting current, a switch for controlling the engine speed when synchronizing, synchronizing plug, and pilot switches for controlling the main generator switches *A* and the selector switches *B*. The ammeters, voltmeters, and other instruments connected with the generators are mounted at *R* on a small panel immediately above the generator pedestal. By mounting the generator controlling apparatus on separate pedestals instead of side by side on panels, the connections are kept separated to better advantage, and the devices are also separated, so that there is less danger of throwing the wrong switches.

The current for exciting the fields of the generators is

supplied from motor-generator sets *S*, each consisting of an alternating-current motor coupled to a direct-current generator. The apparatus for starting and controlling each of these sets is mounted on a pedestal *T*, and the instruments connected therewith are mounted on panels *u* directly above the pedestal. *V* is a low-pressure, direct-current switchboard from which the exciter current is supplied.

From the above it will be seen that a high-pressure switchboard for a large station involves a wide variety of apparatus and occupies a large amount of space. The switchboard used in the large station of the Manhattan Elevated Railway, New York, is similar in its general design and handles current at 11,000 volts. In this station the operating board is equipped with small strips of brass that represent the main bus-bars, and the handles of the switches are so arranged that when moved, they apparently close or open the diagrammatic circuit on the controlling board. Signal lamps are also arranged to show whether a switch is on or off, the whole object being to arrange the controlling board so that the attendant will see just what connections exist between generators and bus-bars, and also what the result will be if certain switches are operated. The object in arranging the controlling board in this diagrammatic fashion is to lessen the danger of confusion when connections have to be rapidly changed—a feature of special importance where large generating units are involved.

82. Fig. 72 shows a switchboard installation for a high-tension station of comparatively small output. This view shows the arrangement of one of the feeder panels. The lever *l*, for operating the feeder switch, is placed on the panel *p* that rests on the floor of the lower switchboard gallery. The levers operate the oil switches *A*, *A* by means of the rods and bell-crank levers, shown in the figure. One of these rods *b* is of wood, so that the operating handle is effectually insulated from the switch. The bus-bars *B* are provided in duplicate and consist of copper rods well insulated with oiled tape. They pass through hard-rubber insulators that are supported by fiber pieces attached to the

angle-iron framework. Each feeder is provided with a current transformer *t*, none of the indicating instruments being connected directly to the high-tension lines. Each feeder is also provided with high-tension enclosed fuses *C*.

83. Fig. 73 shows the general scheme of connections for two of the generators and one of the feeders. This layout may be taken as an example where the generator supplies current at high pressure to the lines without the intervention

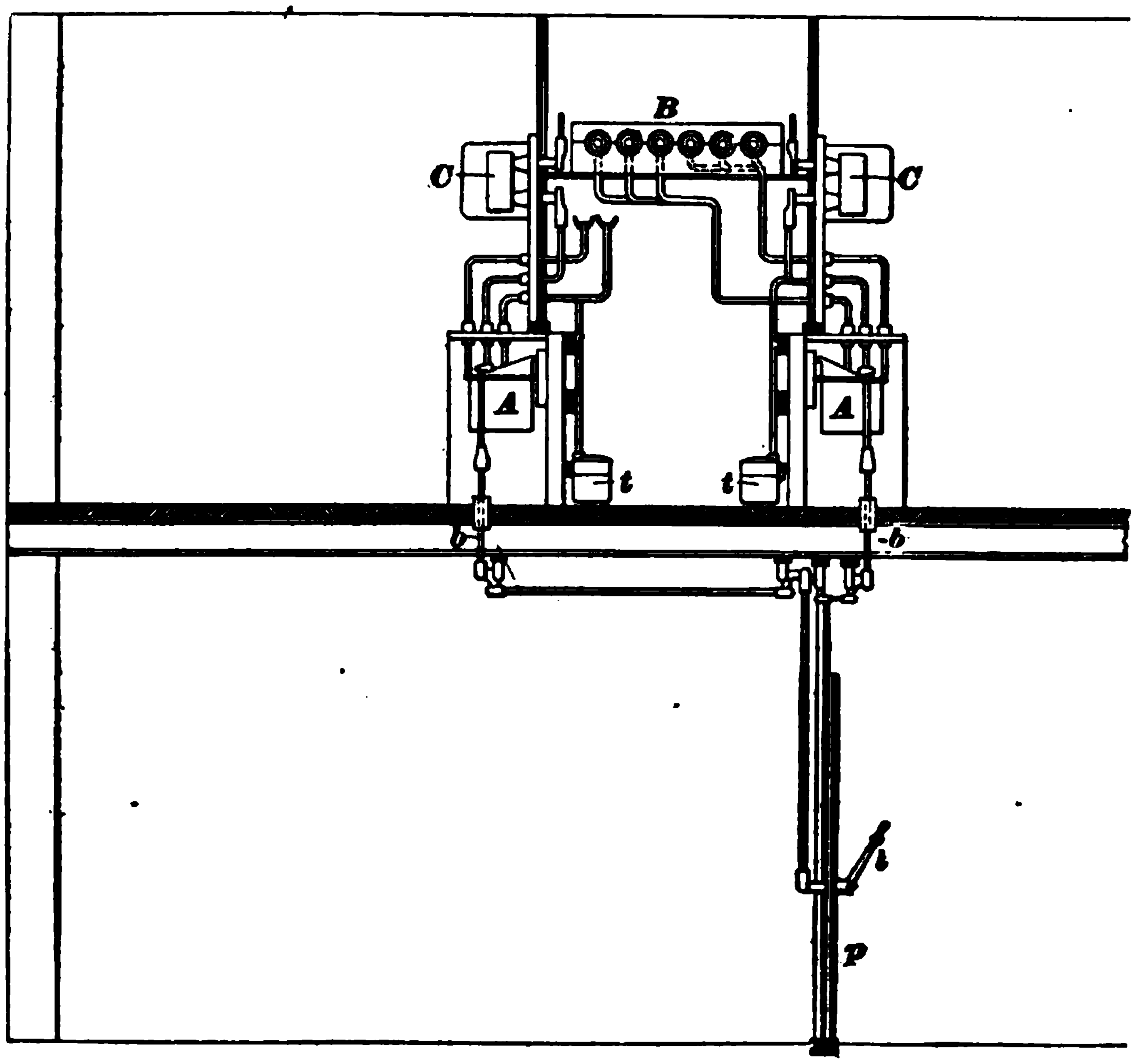
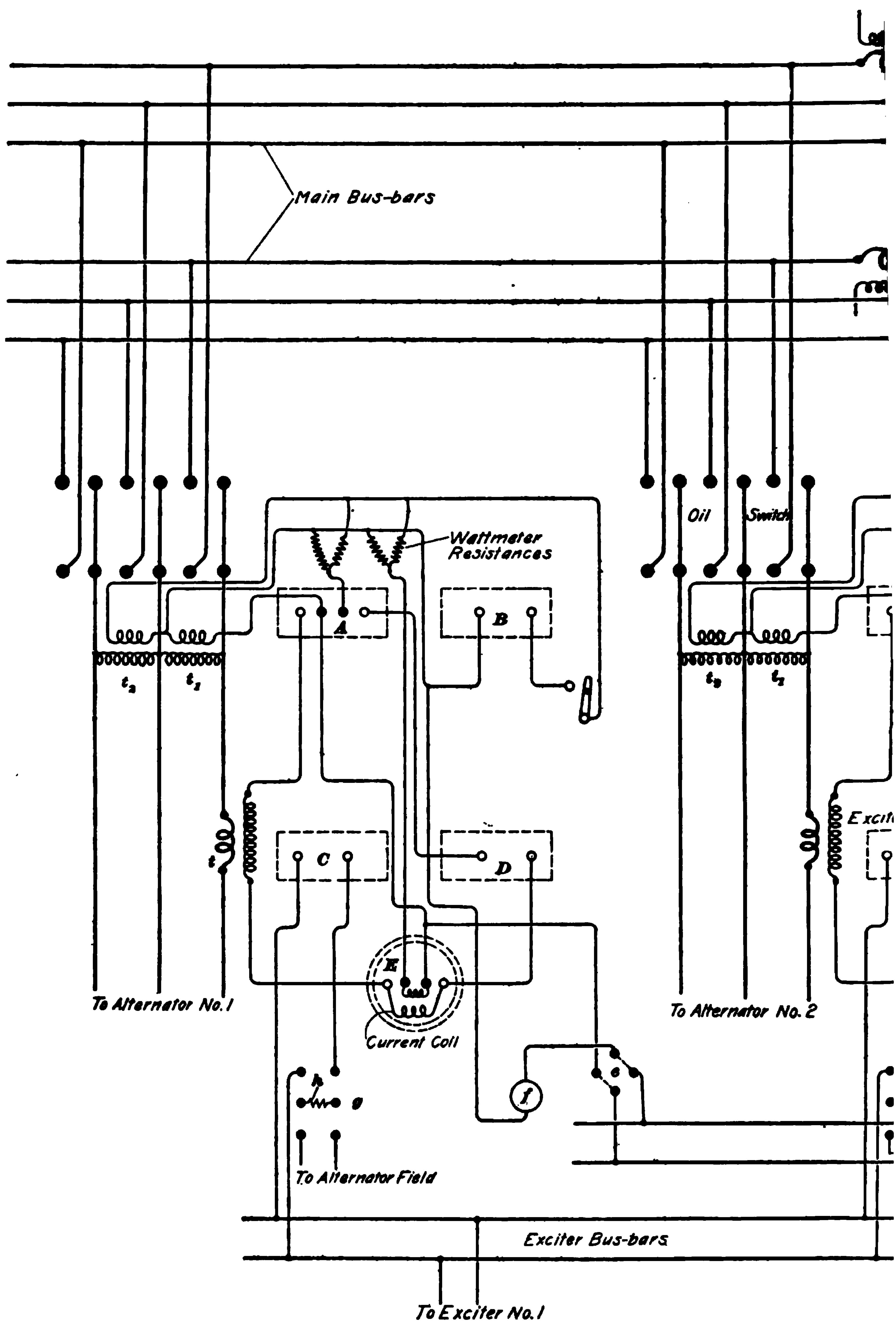


FIG. 72

of step-up transformers. Each generator is provided with an ammeter *D*, supplied from a current transformer *t*, and a voltmeter supplied from a potential transformer t_1. A second ammeter *C* is also connected in the field exciting circuit, so that the field current may be read at all times. The current transformer supplies the current coils of the indicating wattmeter *A* and the recording wattmeter *E*. *A* indicates the watts delivered by the alternator, and *E*

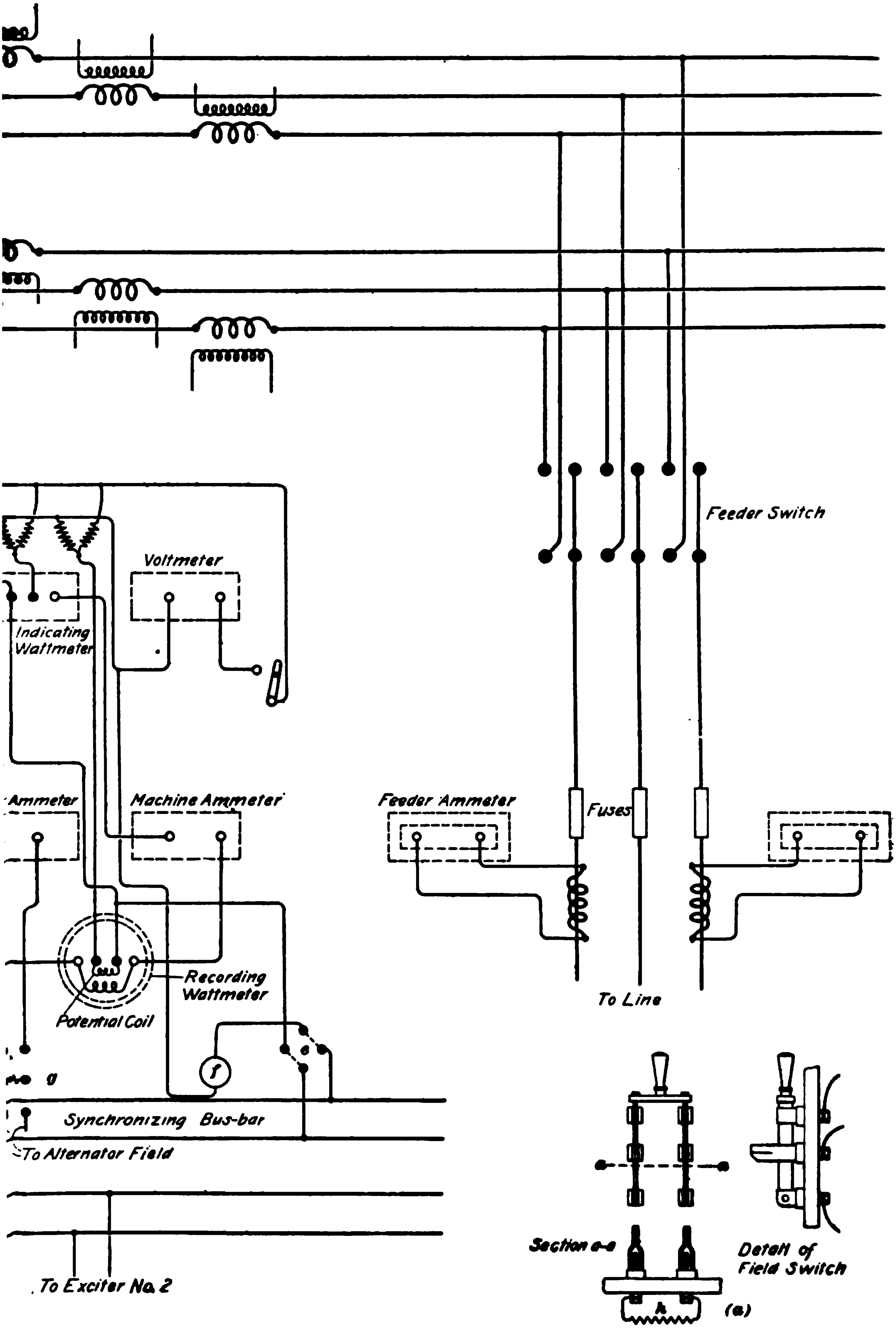
records the watt-hours or kilowatt-hours. The indicating wattmeter indicates the load on each machine, so that the attendant can see at a glance whether or not each machine is taking its share of the load and can adjust the governor on the engine or waterwheel accordingly. The switch *g* is for connecting the alternator field to the exciter bus-bars, and it is provided with two long clips between which a resistance *h* is connected, so that when the switch is opened this resistance is connected across the field terminals, thus taking up the discharge from the field and avoiding the danger of puncturing the field insulation. The construction of this switch is indicated in the small detail sketch (*a*). The long clips are formed so that when the switch is completely closed, the blades connect the lower and upper clips, but do not make contact with the middle clips. The synchronizing plugs are shown at *e*, *e*; and *f*, *f* are the synchronizing lamps. Each feeder running out from the station is provided with an oil switch, fuses, and two feeder ammeters. Sometimes three ammeters are used on the outgoing lines, as an ammeter on each line is often of service in indicating the condition of the line and also in showing whether the load is balanced or not. In some cases the fuses are replaced by automatic circuit-breakers, while in others the switch is provided with an automatic tripping device, so that the switch will open the circuit in case there is an overload or short circuit on the line. Current transformers *K* are connected in the bus-bars between the alternators and the feeders in order to supply total output ammeters.

84. Example of Double-Current Generator Installation.—Fig. 74 shows a simplified diagram of connections for two double-current generators feeding into a three-wire, direct-current system for supplying near-by points and furnishing alternating current, through step-up transformers, to high-tension feeders running to outlying points. All auxiliary apparatus, such as ammeters, voltmeters, etc., is omitted in order to bring out the main connections more prominently. The method of operation shown in Fig. 74 is used by the



Main Bus-bars
Oil
Switch
Wattmeter Resistances
A
B
C
D
E
t_2
t_1
t
Current Coil
To Alternator No. 1
To Alternator No. 2
h
g
e
f
To Alternator Field
Exciter Bus-bars
To Exciter No. 1

Fig


Feeder Switch
Voltmeter
Indicating Wattmeter
Ammeter
Machine Ammeter
Feeder Ammeter
Fuses
Recording Wattmeter
Potential Coil
To Line
f
Synchronizing Bus-bar
To Alternator Field
To Exciter No. 2
Section a-a
h
Detail of Field Switch
(a)

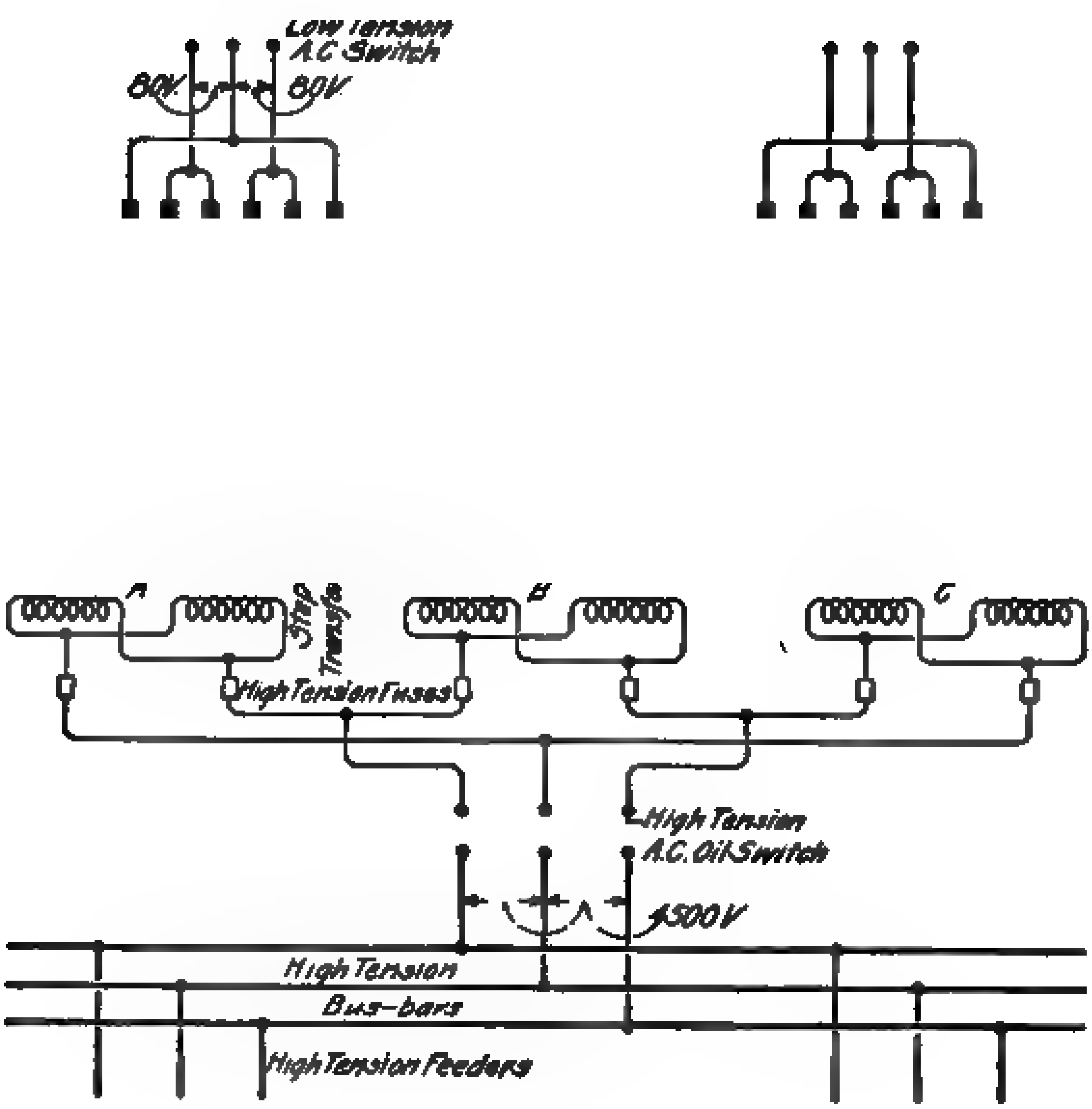

Low Tension
A.C Switch
80V
80V
A
B
C
Step
Transfs
High Tension Fuses
High Tension
A.C. Oil Switch
1500V
High Tension
Bus-bars
High Tension Feeders

FIG. 74

Chicago Edison Company. Two double-current generators are direct driven from a single steam engine and direct current at about 125 volts is supplied from the commutators and three-phase alternating current at from 75 to 80 volts from the collector rings *1*, *2*, *3*. The commutators are connected in series and are attached to the neutral bus-bar. The shunt fields of the generators are arranged for excitation from the direct-current bus-bars, and the + and − brushes of the pair of generators are connected to the + and − bus-bars of the three-wire system. In order to permit independent control of the alternating voltage, potential regulators are inserted, as shown. These regulators are of the induction type described later in connection with the use of rotary converters. After passing through a low-tension switch, the alternating current is led to the primaries of three step-up transformers A, B, C that raise the pressure from 80 volts to 4,500 volts. Each transformer is provided with two primary coils that are connected to two corresponding phases of the generators, as indicated by the numbers on the terminals of the primary coils. Each primary is provided with low-tension fuses. The two secondaries of each transformer are connected in parallel, and the three groups are Δ connected to the high-tension bus-bars. The alternating-current sides of the two double-current generators are therefore connected in parallel through the step-up transformers and feed into common high-tension bus-bars from which alternating current at high pressure is supplied to feeders running to distant centers of distribution. It is thus seen that by using double-current machines, a variety of service can be supplied from a single generating outfit and the generators kept loaded to best advantage.

85. The foregoing will give the student a general idea as to the arrangement of switchboards and the apparatus used in connection with them. The variety of apparatus used in switchboard work is so great that it is impossible to treat all types. Many stations have now become so large that it has been found necessary to make the switchboard

proper simply a place for grouping the small auxiliary devices needed to operate the main devices. It is now common to find field rheostats, field switches, main switches, etc. operated electrically or pneumatically from a distant point, and this method of operation has naturally introduced a large number of new switchboard appliances. Generally speaking, the tendency is to carry on this remote control by means of electricity rather than compressed air, as the electric current has proved just as reliable and is easier to apply. In some cases small electric motors are used for operating switches, rheostats, or other devices, especially where a rotary motion is required. In other cases a solenoid or electromagnet is simpler and more easily applied.

POWER TRANSFORMATION AND MEASUREMENT

TRANSFORMERS AND TRANSFORMER CONNECTIONS

1. Transformers vary somewhat as to their construction, but all have the three essential parts, i. e., the primary and secondary coils or groups of coils and the iron core that

Primary Mains

Suspe

FIG. 1

serves to carry the magnetic flux through the coils. Their construction also depends to some extent on whether they are to be used outdoors or indoors. Fig. 1 shows a typical transformer for outdoor use mounted on a pole in the

usual manner. Where transformers are large, say above 25 or 30 kilowatts capacity, it is not advisable to mount them on poles if it is possible to avoid it.

2. Primary Fuses.—Transformers are operated on constant-potential circuits almost exclusively; hence, if a short circuit occurs on either primary or secondary, there will be a heavy rush of current, which will do damage unless the transformer is instantly disconnected from the circuit. This is accomplished by inserting fuses in the primary between the transformer and the line. The fuses also protect the transformer against overloads. Fuses should be placed in each side of the primary, as indicated at *b*, *b*, Fig. 1, and should be so mounted as to be easily replaced by the lineman. Primary fuse blocks are made so that the fuse holder may be entirely disconnected from the primary mains when the fuse is being renewed; in other words, the fuse block serves the purpose of a switch as well as a fuse holder. In some cases the blocks are double-pole, but when the primary pressure is high, it is better to use two single-pole fuse blocks. Double-pole blocks are not recommended for transformers of greater capacity than 2,500 watts.

(a)

Fig. 2

Fig. 2 (*a*) shows a General Electric double-pole primary switch and fuse block, with one fuse holder (*b*) removed for replacing a fuse. The fuse lies in a deep slot *e* in the porcelain holder (*b*), and is fastened to the clips *d*, *d*. When the holder is in place, the clips engage with the terminals *f*, *f*, thus completing the connection to the transformer primary.

When a fuse is to be renewed, the porcelain base is pulled out and the lineman can replace the fuse without danger.

Fig. 3 shows a single-pole block made by the Stanley Company. In this case, the lid of the iron box is placed at the bottom and the fuse holder *A* is pulled out, thus breaking connection with the terminals *t*, *t*. The fuse *g* runs through

(b)

Fig. 3

a block of wood *h*, thus confining the arc and preventing it from arcing and burning the terminals *t*, *t*.

Where large transformers are operated in substations, automatic switches or circuit-breakers are used instead of fuses to disconnect the transformer from the line in case of a short circuit or overload.

TRANSFORMERS ON SINGLE-PHASE CIRCUITS

3. Transformers in Parallel.—Transformers may be connected in parallel so as to feed a single circuit, as shown in Fig. 4, but care must be taken when making the connections. Suppose that the two transformers are of the same type, so that they will both be wound alike. The primary terminals P_1 and P_2 must be connected to one of the mains, and P_3 and P_4 to the other main; the secondary terminals *a* and *c* will then have the same polarity at the same instant, which is the result desired. It will be noticed that, from the way in which the secondaries are connected, they oppose each other, and that little or no current will flow until the outside circuit is connected. In practice, it will be found that a current will flow between the transformers, but it will not be large. Suppose, however, that the secondary terminals are connected as shown in Fig. 5; the coils are now in series so that the E. M. F.'s act together to set up a current through the coils, thus resulting in a short circuit. In connecting up the secondaries, before making the final connections it is always well to make sure that the proper secondary terminals are being connected together. This can be found out by connecting two of them

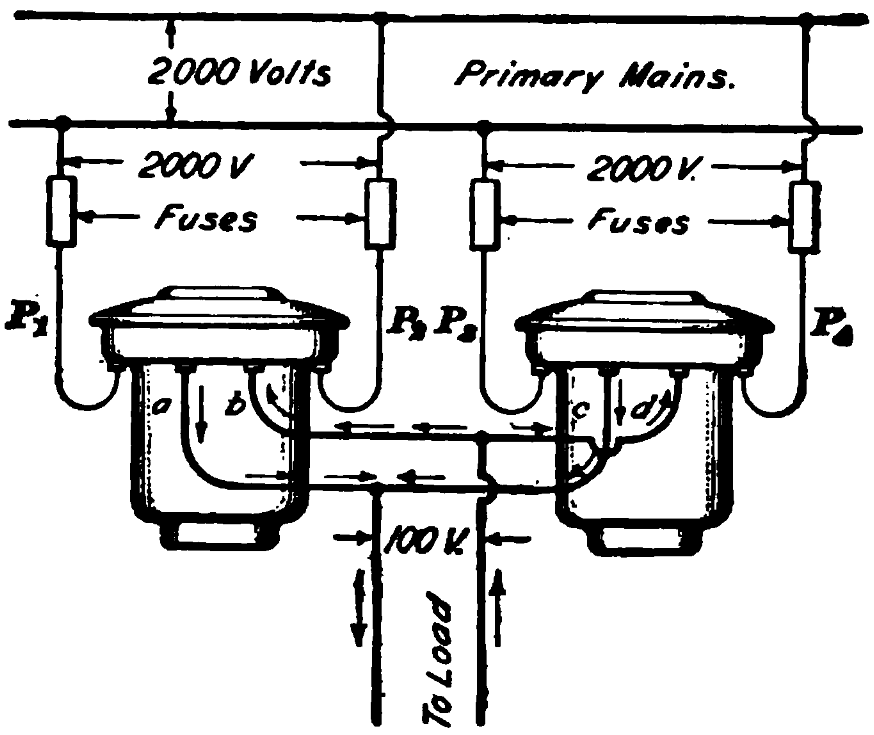


FIG. 4

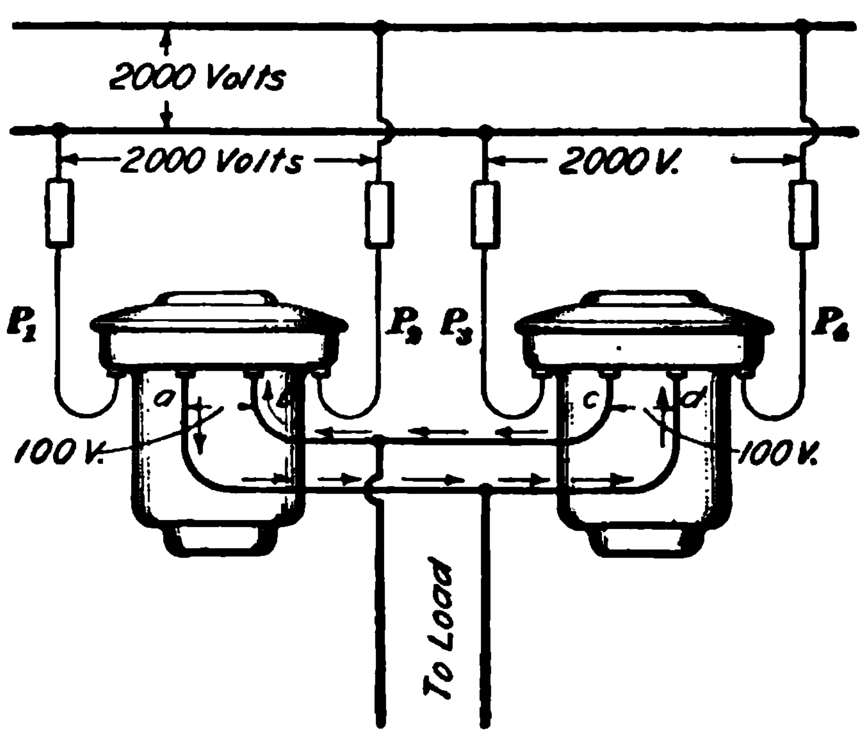


FIG. 5

together and then connecting the other two through a piece of small fuse wire or fine copper wire. If the fuse blows, it shows that the connections should be reversed. It is often more convenient to reverse the primary terminals than the secondary, especially if the latter have been joined up permanently. Reversing the primary has, of course, the same effect as reversing the secondary, and it is usually easier to carry out, because the primary connections are lighter and easier to handle.

4. Generally speaking, it is not advisable to operate several transformers in parallel, or *banked*, as it is sometimes termed. This is especially true if the transformers are

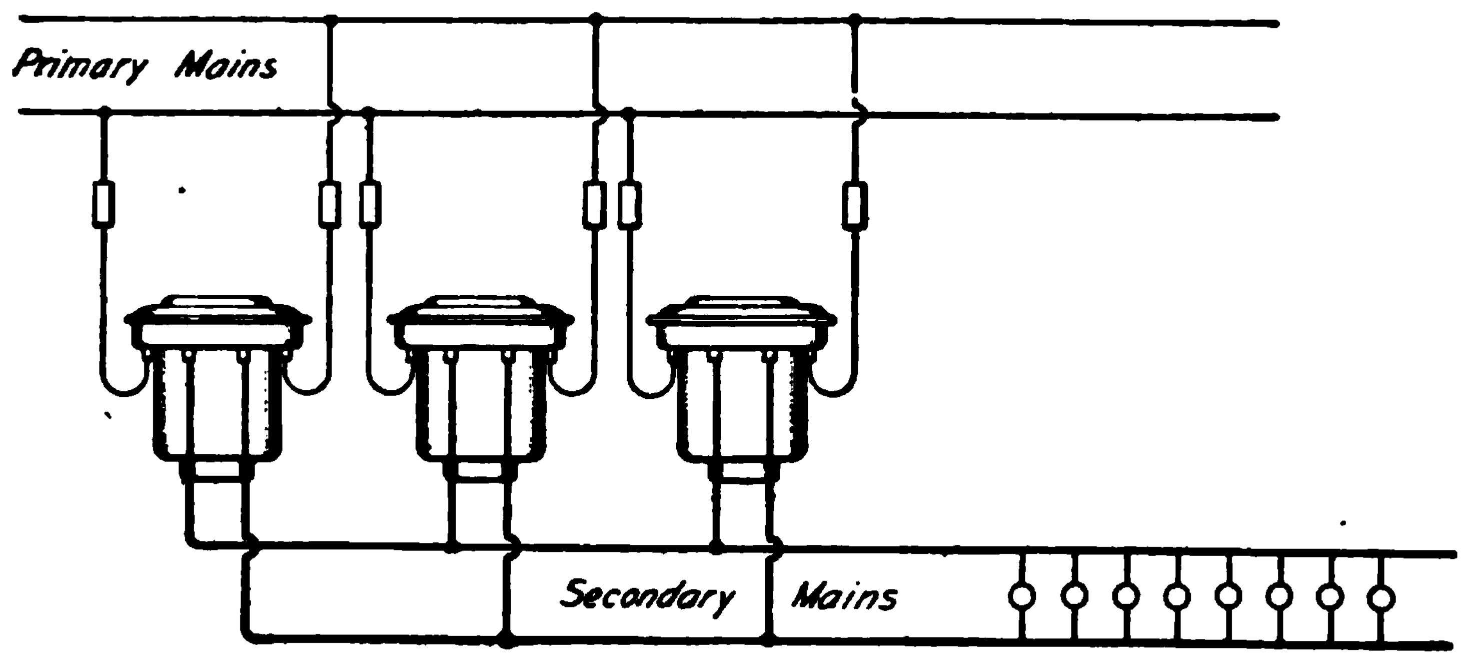


FIG. 6

small and scattered, as on many lighting systems, although it was occasionally done some years ago, when transformers were not made in large sizes. Suppose that a number of transformers are operating in parallel, as shown in Fig. 6. If they do not all have the same voltage regulation, the load may divide unequally between them and one or more of them take more than its share. The result is that the fuses of the heavily loaded transformer blow, and a heavier load is thrown on the remaining transformers, thus blowing their fuses. Of course, if the transformers are all of the same size and of similar design, such trouble is not very likely to happen; but it is better, if possible, to have each transformer supply its own share of the load, and if more capacity

is needed, to use one large transformer rather than a number of small ones.

5. Transformers are very often wound with their primaries and secondaries in two sections, so that they can be connected in series for high voltage and in parallel for low voltage. For example, in Fig. 7 the transformer is wound with two primary coils P, P_1, each designed for 1,000 volts and two secondary coils each wound for 50 volts. By connecting the coils P, P_1 in series, the transformer may be operated on 2,000-volt mains, and if the secondaries are also connected in series, it will supply current to 100-volt secondary mains. If the two primaries P, P_1 are connected in

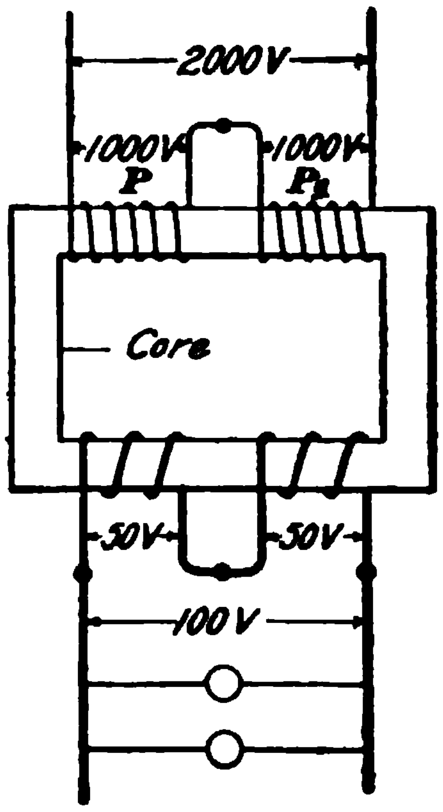


Fig. 7

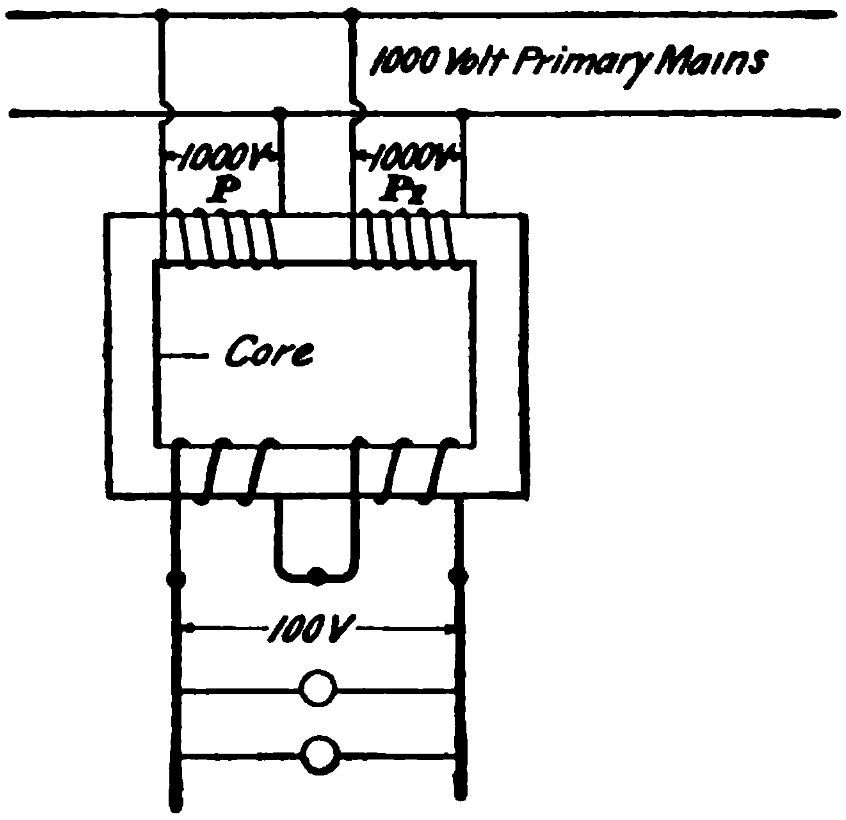


Fig. 8

parallel, as shown in Fig. 8, they may be operated on 1,000-volt mains, and if the secondaries are connected in series, they will supply current at 100 volts. If desired, the secondaries could be connected in parallel to supply current at 50 volts, but the 50-volt secondary circuit has practically gone out of use. A pressure of 50 volts was, at one time, used for incandescent lamps operated from transformers, but has given place to 100 to 110 volts, because the latter pressure requires less copper and it is now possible to obtain 100- to 110-volt lamps that operate fully as satisfactory as those made for 50 volts. Transformers are now

frequently wound so that they can be connected for either 104 or 208 volts on the secondary.

6. In many places, plants that were originally installed to operate at 1,000 volts primary pressure have been changed to 2,000 volts, in order to allow a larger load to be carried without increasing the size of the line wires. In such cases it has been common practice to connect old 1,000-volt transformers in pairs, as shown in Fig. 9.

7. Transformers on the Three-Wire System.—The general tendency is to use a few large transformers for supplying a given district rather than a number of small ones. Small transformers are wasteful of power, and though each in itself may not represent a very large loss, yet when a large number are connected the total amount of energy that might be saved during a year by using a few large transformers may be surprisingly large.

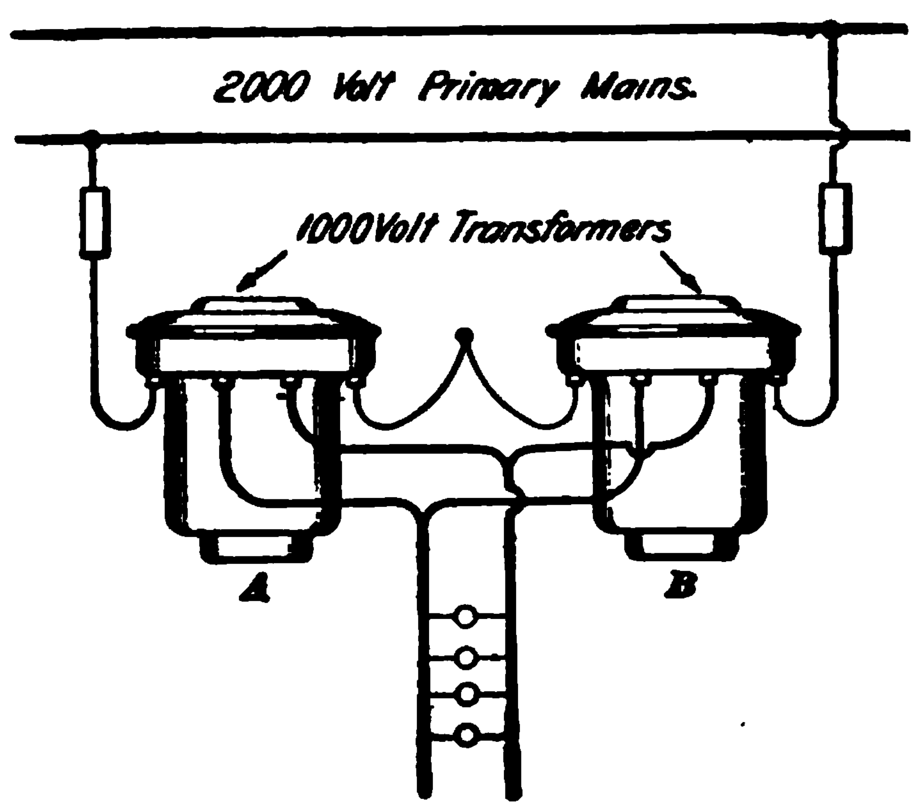


FIG. 9

Of course, in most cases where the customers are scattered it is impossible to avoid using a number of small transformers, but in business districts it is generally easy to use a few large transformers of high efficiency. These are frequently connected in pairs so as to feed into three-wire secondary mains *m*, *m*, *m*, as shown in Fig. 10. The primaries are connected directly across the line in parallel, and the secondaries are connected in series with the neutral wire connected between them at the point *o*. Care must be taken in connecting the secondaries to see that the terminals *a*, *b* are of opposite sign. If they are correctly connected, a pair of lamps *l*, *l* connected in series across the outside lines

should burn at full brightness. If they are wrongly connected, the lamps will not light at all, showing that terminals *a*, *b* are of the same polarity and that *c*, *d* are also the same, the secondaries being connected so that the two outside mains are of the same polarity with a common return wire in the middle. If two transformers are of the same style and make, the terminals of corresponding polarity will usually be brought out of the case in the same way. For example, in Fig. 4, terminals *a*, *c* would be of the same polarity at the same instant. It is always best, however, to test out the connections before connecting permanently, and this is

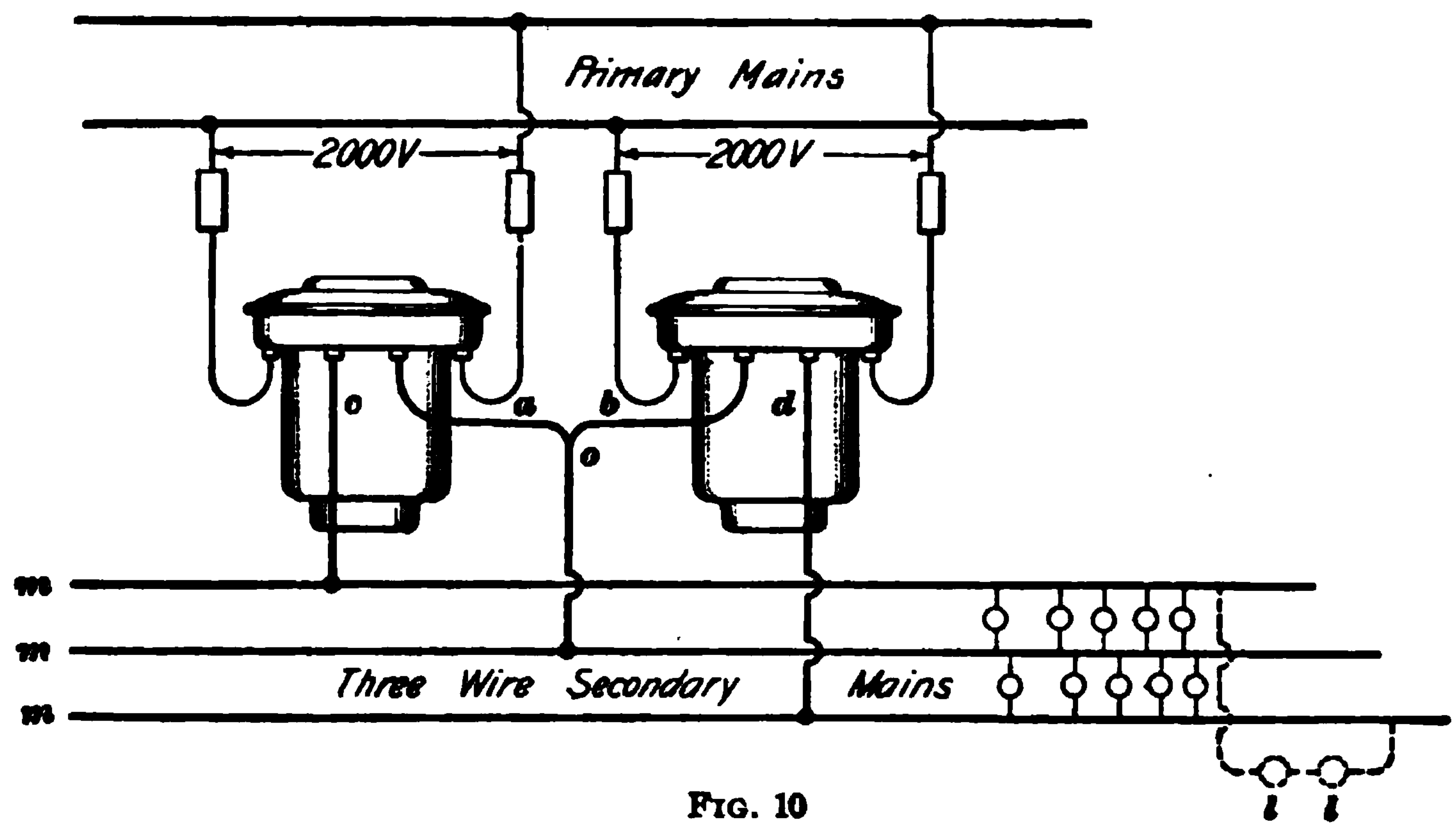


FIG. 10

especially necessary in case two transformers of different make or type are being dealt with.

8. Core-Type Transformers on Three-Wire System. When ordinary transformers of the core type are used to supply current to a three-wire secondary system, as shown in Fig. 11 (*a*), the voltage on the two sides of the circuit may become greatly unbalanced if the load is not equally divided. For example, in Fig. 11 (*a*) take the extreme case where the side *a* is not loaded at all. Secondary coil *s* will have no current and will therefore set up no counter magnetization, whereas coil *s'* will have a current due to the load on side *b*. Thus the magnetic flux in the two sides of the

core becomes unequal, as roughly indicated by the dotted lines, and the secondary E. M. F. is considerably higher on the side *a* than on the loaded side *b*. In order to overcome this difficulty, the General Electric Company wind the secondary in a number of sections *s, s, s, s*, Fig. 11 (*b*), and cross-connect these coils as indicated. The result is that no matter how unbalanced the load may be, the magnetizing effect of the secondary is the same on both cores and the voltage remains practically the same on both sides.

(*a*) (*b*)

FIG. 11

TRANSFORMERS ON TWO-PHASE CIRCUITS

9. As most two-phase circuits are operated with four wires, such a system is practically equivalent to two single-phase circuits. If it is necessary to connect two transformers in parallel, as shown at (*a*), Fig. 12, their primaries must be connected to the same phase. If they are connected to different phases, as indicated by the dotted lines running to phase *1*, a local current will flow through the secondary coils, because the secondary currents will not be in phase and there will be intervals when the E. M. F. of one will be greater than that of the other. The secondaries may, however, be connected in series, as shown at (*b*), forming a

To Load.
(a)

To Load.
(b)

To Load.
(c)

Fig. 12

To Load.
(a)

To Load.
(b)

To Load.
(c)

Fig. 13

kind of three-wire system. If the voltage of each secondary is E, the voltage between the two outside wires will be $E \times 1.414$. This is because the E. M. F.'s in the two coils are not in phase. This method of connecting transformers, however, is not to be recommended, as the voltages on the two sides of the three-wire system are apt to become unbalanced. If a three-wire system is desired, it is better to use the connections shown at (*c*), where both primaries are connected to the same phase. The E. M. F.'s in the two secondary coils are, in this case, in phase with each other and the pressure across the outside wires is twice that of one secondary coil.

10. In connecting transformers to a two-phase system, the aim should be to get the load on the two phases as nearly balanced as possible. Of course, where motors are operated, both phases are used, and, hence, there is not much danger of an unequal division of load. When lamps are connected, one transformer or set of transformers at one point on the circuit can usually be balanced against another group at some other point, so that the load as a whole will be equally divided. Fig. 13 shows different methods of connecting transformers on a two-phase system, using three line wires. In this case the central wire acts as a common return, and the voltage between the outside wires is 1.414 times that of each phase. The same remarks apply here as in the previous case, and the three-wire arrangement shown at (*b*) is not as generally satisfactory as that shown at (*c*). In both cases the primary pressure is shown as 2,000 volts, and transformers with a ratio of 20 to 1 are taken for the sake of illustration.

TRANSFORMERS ON THREE-PHASE CIRCUITS

11. Until recently it has been customary in America to use three single-phase transformers for transforming from one pressure to another on three-phase circuits; the three transformers may be connected up either Y or Δ. With the Δ arrangement, the power supply will not be entirely

(d)

Fig. 14

crippled even if one of the transformers should become damaged; also transformers wound for standard line voltages can be used. In some cases, however, the primaries are connected across the lines according to the Y scheme, as shown at (*a*), Fig. 14, and since there are two primary coils in series between any pair of mains, the pressure on any one primary coil is less than that between the mains. When the primaries are Y connected, the secondaries are usually Y connected also, as shown at (*a*). Sometimes, however, the primaries are Y connected and the secondaries Δ, as shown at (*b*). If transformers having a ratio of 20 to 1 were connected in this way, the secondary pressure would not be the primary pressure divided by 20, i. e., 100 volts; but $\frac{100}{1.732}$, or 57.7 volts. In order to get 100 volts secondary with this scheme of connections, the transformers would have to be wound with a ratio of $\frac{20}{1.732}$ to 1, i. e., 11.55 to 1, approximately. Fig. 14 (*c*) shows transformers with both primaries and secondaries Δ connected. The arrangements shown at (*a*) and (*c*) are the ones commonly used for three-phase work, as scheme (*b*) either calls for special windings on the transformers or else gives rise to odd secondary voltages. If the primaries are to be Δ connected, each primary coil must be wound for the full-line voltage. If the primaries are Y connected, each primary coil is wound for the line pressure divided by 1.732. It is possible to use only two transformers on a three-phase system, as shown in Fig. 14 (*d*), but this arrangement is not, on the whole, as desirable as the Δ connections, because if one breaks down the service is crippled. It is equivalent to the delta arrangement with one side left out. The connections shown in (*c*) are used more largely than any of the others.

12. Phase-Changing Transformers.—By combining two E. M. F.'s that differ in phase by 90°, an E. M. F. of any desired amount and phase relation to the original E. M. F.'s can be obtained. For example, in Fig. 15 (*a*), suppose it is desired to produce an E. M. F. E of the amount represented

by the line *oc* and having the phase relation of *oc*. This E. M. F. can be regarded as made up of the two components *ob* and *oa* at right angles to each other; hence, if two E. M. F.'s E_1 and E_2, having the values represented by the lines *ob* and *oa*, and differing in phase by 90°, are combined, the result will be the required E. M. F. E. In Fig. 15(*b*), A and B are the primaries of two transformers connected to a two-phase system. The E. M. F.'s E_1 and E_2 induced in their secondaries will therefore differ in phase by 90° and E_1 and E_2 can be made any desired value by suitably

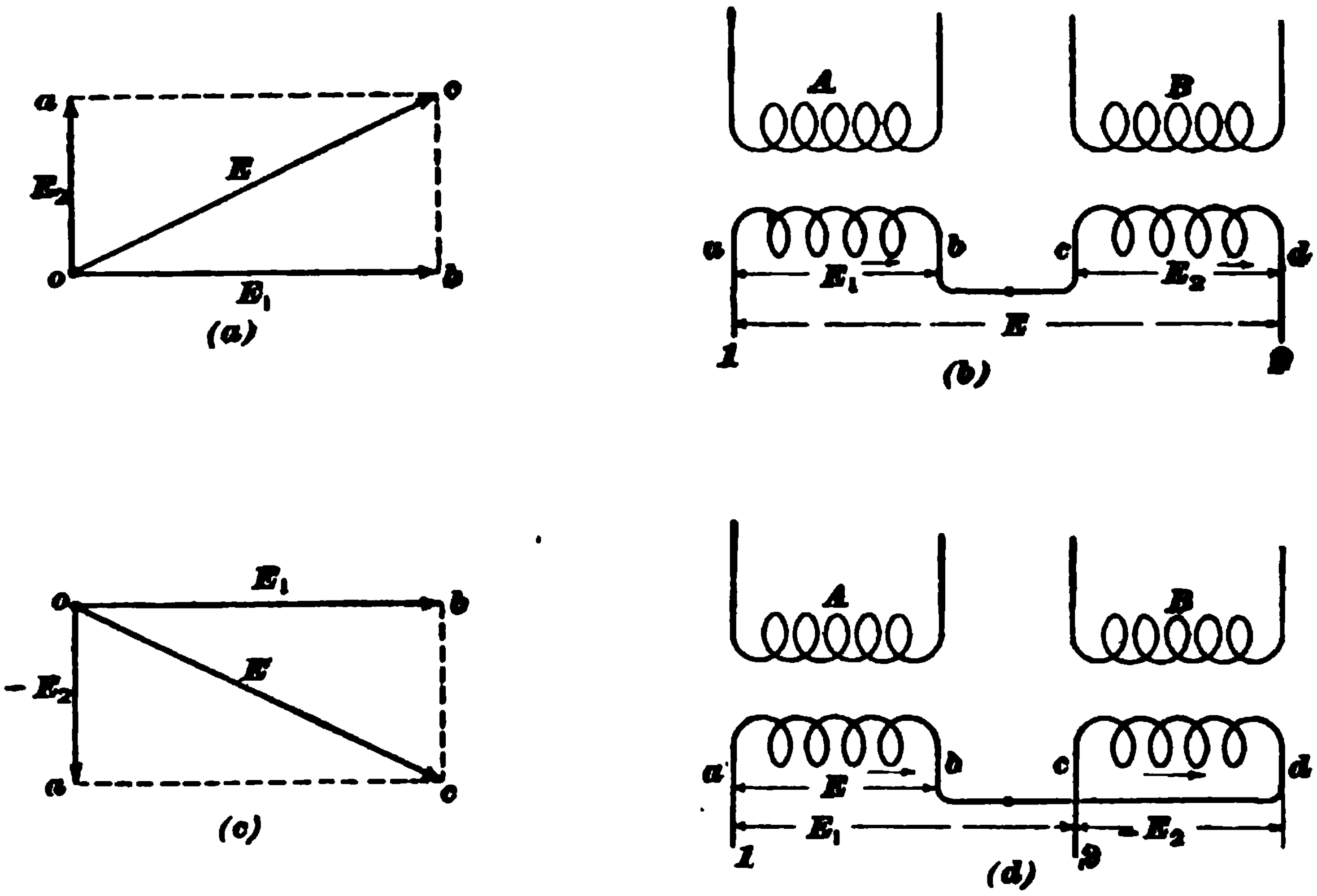


FIG. 15

proportioning the windings. If the two secondaries are connected in series, the E. M. F. between the lines will be the geometric sum of E_1 and E_2, as shown in (*a*). For example, in (*b*), in passing from line *1* to line *2* we go through each coil in the same direction; that is, we pass from *a* to *b* and from *c* to *d* in the direction indicated by the arrows. We will call this the positive direction. In (*d*), in passing from *a* to *b* we go through the coil *a b* in the positive direction, but, with the connections of the second coil reversed, as shown, we pass through *c d* from *d* to *c* against the arrow. The line *o a* (*c*) is therefore reversed with regard to its position in (*a*) and

the E. M. F. E between lines *1* and *2* is now denoted by the line oc, which is the same in amount as in (a), but has a different phase relation. Fig. 15, therefore, shows a method of obtaining a single phase current of any desired amount or phase relation, from two currents differing in phase by 90°.

13. Scott Two-Phase, Three-Phase Transformer. One of the most common examples of phase transformation is the changing of two-phase currents to three-phase, or vice versa, by means of the arrangement devised by Mr. C. F. Scott. In Fig. 16 (a), A and B are the primary coils of two transformers connected to a two-phase system. The secondary of A, i. e., the coil ac, is provided with a winding such

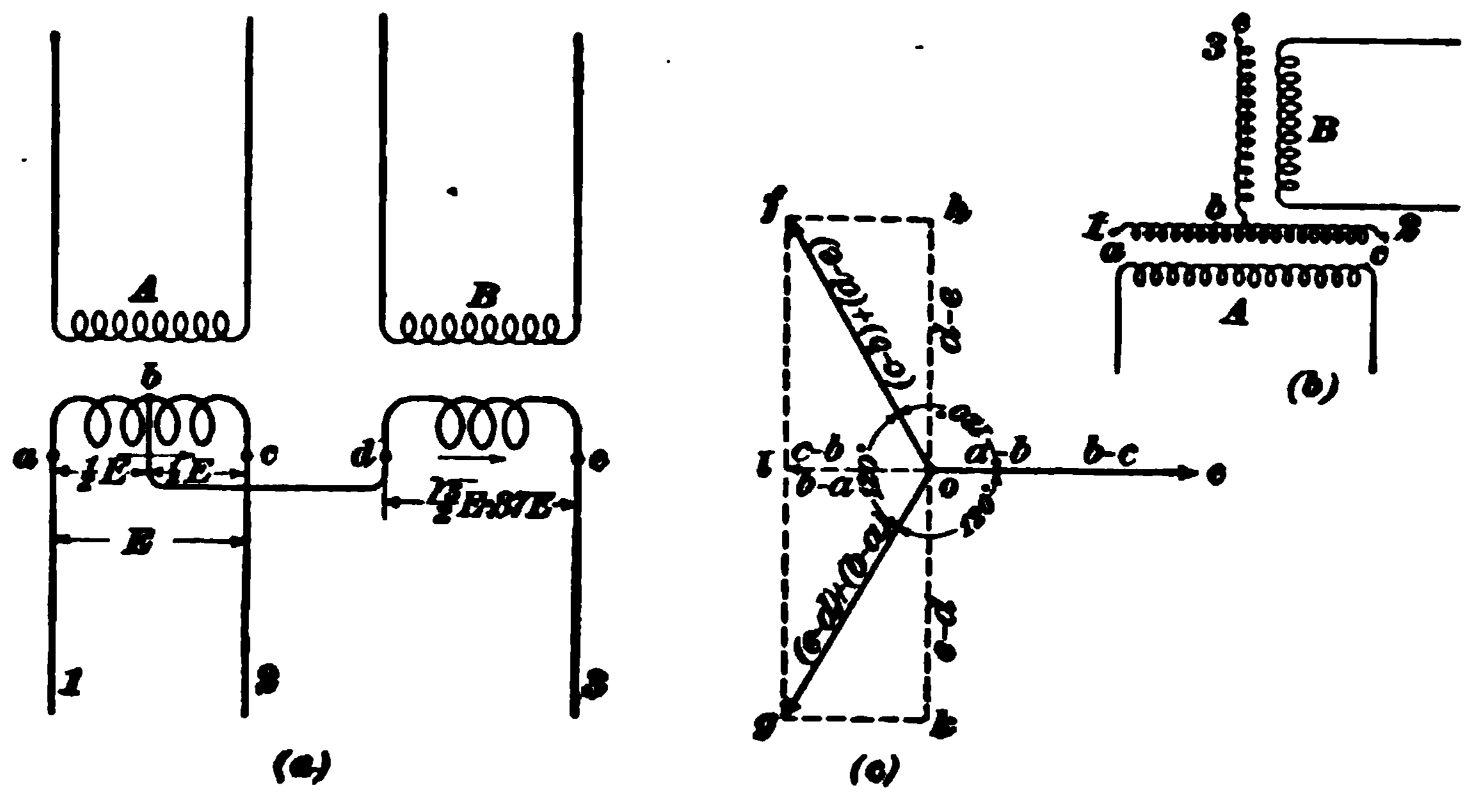


FIG. 16

that its voltage E will be the required voltage of the three-phase system. The secondary of B has $\frac{\sqrt{3}}{2}$ or .87 times as many turns as the coil ac, so that the voltage generated in it is .87 E. One end of coil de is connected to the middle point b of coil ac, as shown. With this arrangement of windings and connections, three currents differing in phase by 120° will be delivered to lines *1*, *2*, *3* when the primaries are supplied with two currents differing in phase by 90°. The same connections are shown in a simplified form in (b), the three-phase lines being attached to points *1*, *2*, and *3*. The E. M. F. between *1* and *2* is that generated in the secondary

ac. The E. M. F. between *2* and *3* is the E. M. F. generated in *bc* combined with the E. M. F. generated in *be*. The E. M. F. between *3* and *1* is that in *eb* combined with that in *ba*. It must be remembered that the E. M. F. in *be* is at right angles to the E. M. F.'s in *ab* and *bc*. Coming back to (*a*) and noting that the positive direction through the coils is marked by the arrows we can lay off the line *oe* in (*c*) to represent the E. M. F. between lines *1* and 2. The E. M. F. between points *a* and *b* is marked $a - b$ in (*c*) and is represented by one-half of *oe*. Also, the E. M. F. between *b* and *c* would be represented by $b - c$. The – sign does not here signify subtraction; it simply denotes that the E. M. F. referred to is taken between the points *b* and *c*. The E. M. F. between lines *2* and *3* is found by adding, geometrically, the E. M. F. $d - e$ to $c - b$. In passing from line *2* to *3* we pass from *c* to *b* against the arrow, or in other words the E. M. F. $c - b$ is the equal and opposite of $b - c$ and is represented by *ol* in (*c*) equal to one-half of *oe*, but drawn to the left of *o*. Coil *de* is passed through in the positive direction so that the E. M. F. $d - e$ will be represented by the line *oh* above the horizontal, and the E. M. F. between lines *2* and *3* will be the resultant of *ol* and *oh*, or *of*. The E. M. F. between lines *3* and *1* is $e - d$ combined with $b - a$. The E. M. F. between *e* and *d* is the equal and opposite of that between *d* and *e*; hence, it is represented by *ok*, which is equal and opposite to *oh*. The E. M. F. $b - a$ is equal to and in the same direction as $c - b$; hence, it is represented by *ol*, and the resultant of *ol* and *ok* is *og*, which is the pressure between lines *3* and *1*. The three secondary-line pressures represented by the lines *oe*, *of*, and *og*, are therefore of equal amount and differ from one another in phase by 120°, as is required for a three-phase system.

For long transmission lines, it is more economical to use the three-phase than the two-phase system; hence, where power is generated by two-phase alternators and stepped up for transmission over long distances, as, for example, at Niagara, the current is often transformed from two-phase to three-phase as just explained.

14. Capacity of Transformers on Two- and Three-Phase Systems.—When transformers are connected on a two-phase system each transformer must be of capacity sufficient to carry half the load. If the three-phase system using three transformers is used, each transformer must be capable of carrying one-third the load. When the transformers are used to operate induction motors, a safe plan to follow is to install 1 kilowatt of transformer capacity for every horsepower delivered by the motor. Thus, a 20-horsepower, two-phase, induction motor will require two 10-kilowatt transformers; a 30-horsepower, three-phase motor will require three 10-kilowatt transformers; and so on. Table I, issued by the General Electric Company, shows the size and number of transformers suitable for 60-cycle, three-phase induction motors.

TABLE I

CAPACITY OF TRANSFORMERS FOR THREE-PHASE INDUCTION MOTORS

Horsepower of Motor	Capacity of Transformers Kilowatts	
	Two Transformers	Three Transformers
1	.6	.6
2	1.5	1.0
3	2.0	1.5
5	3.0	2.0
$7\frac{1}{2}$	4.0	3.0
10	5.0	4.0
15	7.5	5.0
20	10.0	7.5
30	15.0	10.0
50	25.0	15.0
75		25.0

SUBSTATION EQUIPMENT

15. General Features.—The high-tension alternating current, for large transmission systems, is usually delivered to a number of substations rather than to scattered groups of transformers, and it is therefore necessary to study the equipment of these substations. In some cases the power is delivered from the substation in the shape of alternating current; in others, it is transformed to direct current and delivered to the various receiving devices, such as lamps, motors, etc. Part of the output may be delivered as direct current and part as alternating, either at the same frequency as the current generated in the main station or at a different frequency. It is thus seen that the character of the equipment in a substation may vary greatly, and will depend on the character of the service. If the power is used for operating a street railway where direct current at a pressure of 500 to 600 volts is required, the substation must be equipped with rotary converters for changing the alternating current to direct. Also, since the alternating current is transmitted at high pressure, it is necessary to provide transformers to step-down the incoming line voltage to an amount such that the converters will give the required direct-current voltage. The current can also be transformed from alternating to direct by using motor-generator sets, i. e., sets consisting of an alternating-current motor connected to one or more direct-current generators. Motor generators are more expensive than rotary converters of equal output, and are not quite so efficient; hence, the latter, especially in America, are much more generally used. For some classes of work, motor generators have advantages, and their operation on fairly high frequencies, over 60 cycles, is more satisfactory than that of rotary converters. They are used considerably on 60-cycle systems where the direct current is used for lighting work which requires close

voltage regulation. In a motor-generator set the two sides of the system are entirely separated, and disturbances on one side are not so liable to affect the other as with rotary converters. It is often practicable to wind the motor to take the high-tension line current without the intervention of step-down transformers, but even allowing for this the motor generator is not as economical, either as regards first cost or efficiency of operation, as the rotary converter. By using frequencies from 40 to 25 cycles per second, little difficulty is found in operating rotary converters; and at these frequencies they are largely used for the conversion of alternating current to direct current, or vice versa.

16. In some cases the output of a substation is delivered wholly as alternating current, and the substation contains simply the static transformers needed for raising or lowering the pressure, together with the switchboard appliances used to control the incoming and outgoing current. In substations where the output is in direct current supplied to lighting or railway systems, it is common practice to provide a storage battery in order to equalize the load, the battery being charged during intervals of light load and discharged when the heavy load comes on. The use of a number of substations supplied from one large central station results in a comparatively constant load on the central station, especially when storage batteries are used in those substations that are situated in densely populated districts and are called on for a very heavy output at certain hours during the day. One of the chief advantages in supplying the power from a large central station is the uniformity of load obtained throughout the day, thus allowing the generating units to be worked at their best efficiency.

The equipment of a substation may be conveniently considered under three heads, namely: (*a*) Apparatus for Controlling the Incoming Current; (*b*) Apparatus for Transforming the Current; (*c*) Apparatus for Controlling the Outgoing Current.

APPARATUS FOR CONTROLLING THE INCOMING CURRENT

17. The apparatus for controlling the incoming current is generally grouped on a regular high-tension switchboard, and is separated, at least so far as the high-tension parts are concerned, from the devices controlling the outgoing current. If lightning arresters are used, they are placed at a point near where the wires enter the building; very often they are placed in a separate building. The arrangement of the controlling devices, of course, differs in different stations, but the incoming lines should first pass through a circuit-breaker or main switch so that all current may be cut off from the station. In many cases oil switches are used, and are so arranged that they may be either opened by hand or automatically whenever the current exceeds the allowable amount. Arranged in this way, the switches fulfil the requirements of both a circuit-breaker protecting the apparatus in case of overload, and a main switch that can be opened by hand when desired. Switches of the air-break type and those in which the arc is broken in a confined air space are also made to operate automatically in case of overload; all of these types are in common use for protecting the incoming lines.

18. Time-Limit Relay.—In most substations, especially in those where rotary converters are operated, it is not desirable to have the circuit opened every time there is a momentary overload, because it allows the converters to fall out of synchronism and it takes some time to get things under way again. Besides, momentary overloads will not, as a rule, damage anything, while a long continued overload or short circuit will. For these reasons it is advisable to equip the circuit-breakers, or automatic switches, on the incoming lines with a **time-limit relay**, which controls the current in the tripping coils and will not allow the circuit to be opened until a certain interval of time has elapsed after the occurrence of the short circuit or overload. If the overload should pass off during this interval, the relay goes

back automatically to its initial position, and the circuit is not opened. If, however, the overload should continue beyond the limit for which the relay is set, contact is made and the tripping coils energized, thus opening the circuit.

Time-limit relays have been made in a variety of forms. Fig. 17 shows one type intended for two-phase or three-phase circuits and used on a number of the Niagara lines. The coils *a*, *a* are connected to the secondaries of current transformers whose primaries are in series with the main lines. If the current in either phase exceeds the allowable amount, either one or both of the armatures *b*, *b* are pulled down, thus releasing the clockwork mechanism *c*. If the short circuit or overload is not removed within the time limit for which the relay is set, say 3 to 5 seconds, the clockwork makes a contact that allows current to flow through the tripping coil of the circuit-breaker and thus opens the circuit. If the overload or short circuit should disappear during the time limit, the armatures *b*, *b* rise, thus preventing the clockwork from making contact. By equipping the various circuit-breakers on a system with this attachment, it is possible to set them so that in case a short circuit or overload occurs on a certain section, the circuit-breaker nearest that section will go out before those nearer the station. In other words, the breakers near the station are set so as to hold on for a longer interval than the more distant ones, thus preventing a shut-down of the machinery due to some fault on a distant part of the system. The time that must elapse before the relay makes contact

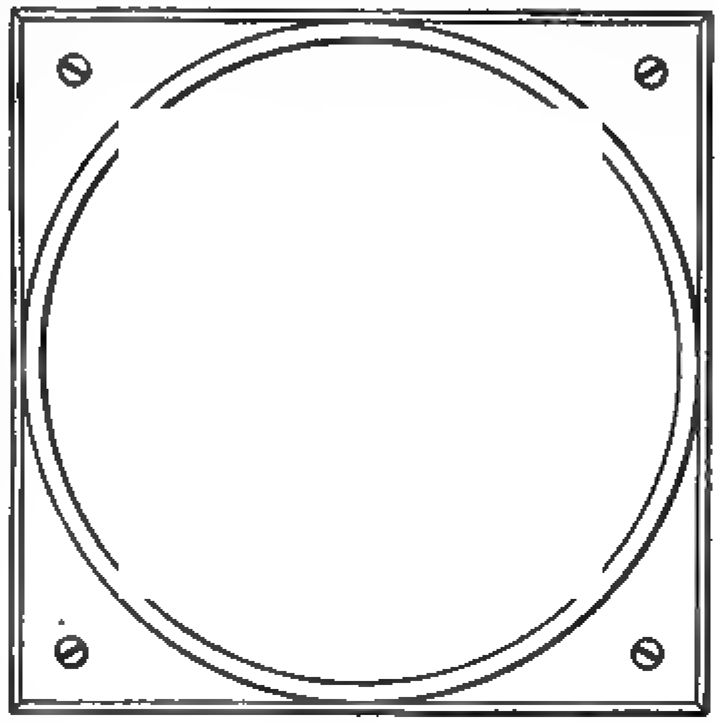


FIG. 17

can be adjusted by varying the angle made by the vanes *d*, Fig. 17. Fig. 18 shows the connections for one type of high-tension circuit-breaker operated by a time-limit relay. Current is supplied to the coils of the relay by the secondaries of the current transformers *A*, *A'*. The incoming lines are attached to studs *a*, *a* of the circuit-breakers, and the main current crosses over to studs *b*, *b* by way of the laminated contacts *c*, *c*, which are forced up against the studs when the breaker is set. Each pair of contact studs *a b* is shunted by a long enclosed fuse mounted in holders so that it can be quickly replaced by a new one in case it blows. When the breaker opens, thus withdrawing *c* from *a* and *b*, the main current flows momentarily through the fuse and the circuit is, therefore, finally opened by the fuse, which is capable of taking care of the arc. If the current becomes excessive and holds on beyond the time limit for which the relay is set, contact *d* touches *e*, thus allowing the cells *f* to send a current through the tripping coils of the breaker.

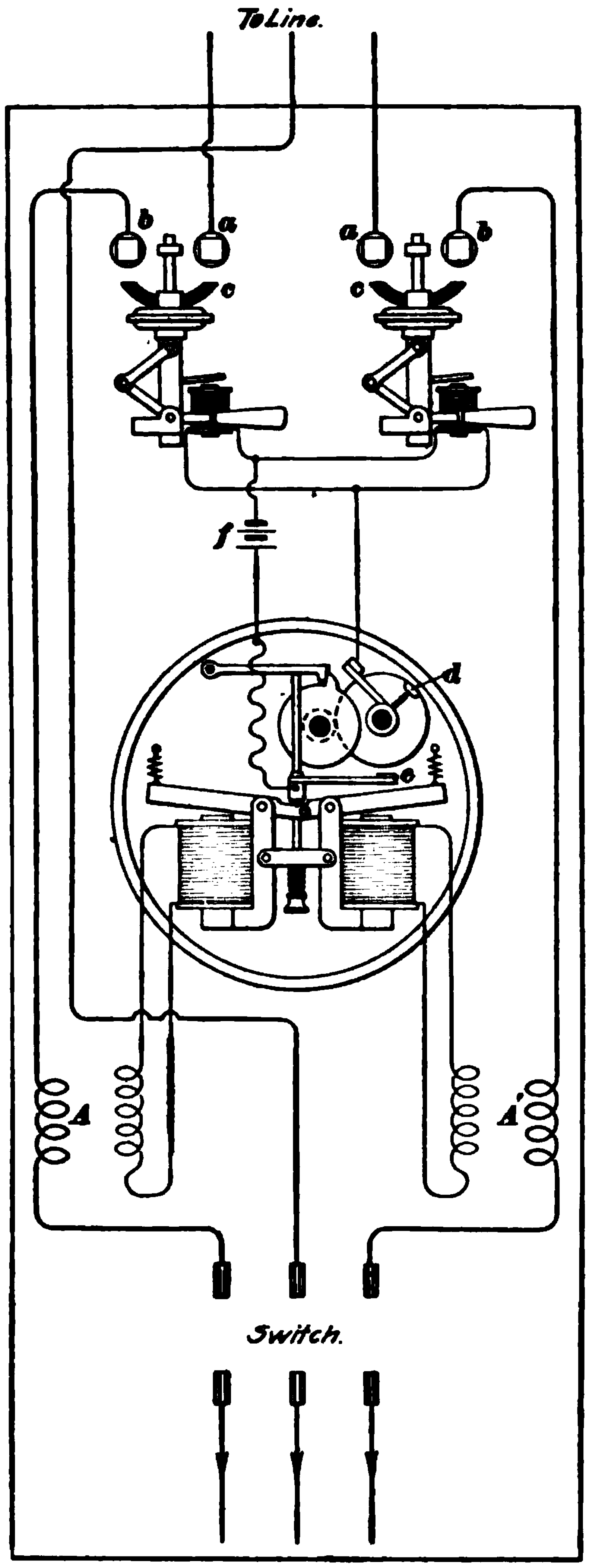


Fig. 18

19. Westinghouse Time-Limit Relay.—Fig. 19 shows a relay made by the Westinghouse Company. In this case the time-limit feature is regulated by means of a dashpot. A solenoid *a* is connected to the secondary of the current transformer, and the movable core *b* rests on a lever *c* pivoted at *d*. To the end of *c* is attached the piston rod *e*, which carries the piston of the dashpot *f*. The lever *c*, counterbalanced by the weight *g*, is normally held in the position shown in the figure, by the weight of core *b* resting on it. The arm *h*, also pivoted at *d*, carries the contact springs *k*, *l* and its position can be adjusted, up or down, by an adjusting screw on the cover of the instrument. Lever *c* carries a contact piece *m* that connects *k*, *l* if lever *c* rises far enough. When the current in *a* exceeds the allowable amount, core *b* is lifted, thus allowing the counterweight *g* to raise lever *c*. The movement of *c* is controlled by the dashpot *f* and the time during which the overload may exist before the circuit is opened is determined by the position of arm *h*. When lever *c* has moved high enough to make contact between *k* and *l*, the circuit-breaker is tripped and the main circuit opened. Should the overload pass off before the time limit is reached, *b* drops back and lever *c* is forced down before it has had time to make contact between *k* and *l*.

Fig. 19

20. Reverse-Current Relay.—In a large distributing system where a number of substations are connected to the main station, and to each other, by a network of cables, it is necessary to provide some means for preventing current

from flowing back toward a defective part and thereby maintaining a short circuit. This point will be understood more clearly by referring to Fig. 20, where *A* is the main station from which current is supplied to the substation *B*. Usually a number of cables in parallel are run between the main station and the substations in order to allow the use of cables of reasonable dimensions, and also to provide for uninterrupted service in case one or more cables should break down. Suppose that *c* and *d* represent two three-wire cables, supplying the substation *B* with three-phase current. When both are in use, the ends at the substation and at the main station are connected to common bus-bars. Suppose that a short circuit occurs at *f* on cable *c*. The rush of current through

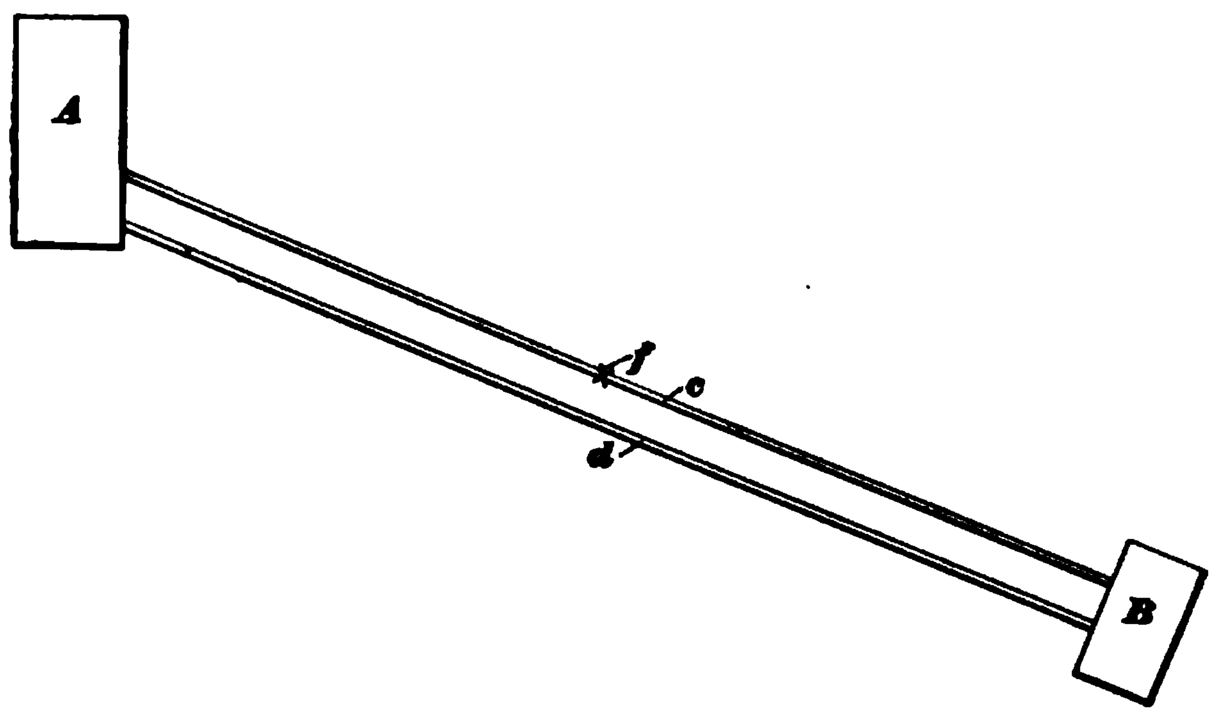


FIG. 20

the fault will, of course, open the circuit-breaker on cable *c* at the main station, but since *d* and *c* are connected together by the substation bus-bars, there is nothing to prevent a heavy current from flowing out over *d* and back through *c* to the fault *f*, thereby causing the circuit-breakers of cable *d* to open and completely shut off the power from the substation. In order to prevent this, **reverse-current relays** are installed at the end of the feeders, and their duty is to trip the circuit-breakers the instant the flow of energy through any of the cables reverses. Of course, where a substation is supplied by a single set of feeders and furnishes current to a secondary system which is not capable

of feeding current back to the line, reverse current relays are not needed.

Fig. 21 shows an arrangement of reverse-current relays used on the Niagara system, and also in a number of other installations. *A*, *A* are the circuit-breakers, and *B*, *B* the reverse-current relays. These relays are similar in construction to small direct-current motors having laminated fields. The field windings are excited by current from the secondaries of two potential transformers t, t', and the armatures are supplied with current from the current transformers c, c'. The armatures are not allowed to turn, since their motion is limited by an arm playing between two stops as shown. When the current is flowing in its normal direction from the cables to the bus-bars, the arm of the relay bears against the lower stop, which is not connected electrically to any other part. If, however, the flow of energy is from the bus-bars to the cables, the flow of current at each instant in the armature is reversed with respect to that in the fields. and the armature at once swings around in the opposite direction until the arm touches the upper stop, thus closing the battery circuit and tripping the circuit-breaker.

Fig. 21

This feeding-back action can also occur, if reverse-current circuit-breakers are not used, where a substation supplied through even a single set of feed-wires runs rotary converters which, on their direct-current side, are in parallel with storage batteries. If a short circuit occurs on the cable and it is cut off from the main generating station, the converters can still operate with direct-current furnished by the battery. They thus run inverted, taking the direct current from the batteries, converting it into alternating current, and feeding back to the line through the transformers. The current thus fed back to the fault in the cable will be very large, and may cause injury to the apparatus if means are not taken to prevent it by means of reverse-current circuit-breakers.

APPARATUS FOR TRANSFORMING THE CURRENT

21. If the current supplied from the substation to the consumers is utilized as alternating current, the substation is equipped with step-down transformers that supply alternating current directly to the secondary network. If the current is utilized as direct current, it is necessary to install rotary converters or motor generators in addition to the step-down transformers.

22. Substation Transformers.—Transformers used in substations do not differ materially from ordinary transformers except as regards their size and the methods used to secure cool running. They are usually of very large output as compared with those used for ordinary local lighting and power distribution. Their efficiency is very high, but on account of the comparatively small radiating surface that they present to the air, it is necessary to provide special means for getting rid of the heat, either by means of an air blast or by water that circulates through a coil of pipe placed in the upper part of the transformer case. With the latter method, the transformer case is filled with oil, and as the heated oil rises to the

upper part of the case it is there cooled by the water in the pipes, and descends to the lower part, thus keeping up a continuous oil circulation that carries the heat away from the coils and core.

Fig. 22 shows a Westinghouse 2,250-kilowatt substation transformer; (*a*) shows the coils and core assembled before being placed in the case. The core laminations *a*, *a* are built with openings *b*, *b* at intervals so that the oil can circulate through the core and conduct the heat from the internal parts. The primary and secondary coils are each wound in several sections in the form of large flat coils, which are then sandwiched together, making a construction that reduces magnetic leakage, and at the same time cuts down the voltage generated in any section of the winding. The ends of the coils project beyond the laminations at the top and bottom as shown at *c*, and the terminals of the coils lead to a terminal board mounted on top. The transformer is placed in a cylindrical tank made of riveted boiler plate, Fig. 22 (*b*), and is completely submerged in oil. Four coils of pipe placed in the upper part of the tank are connected in parallel by pipes *a*, *a* attached to common inlets and outlets. Each coil is provided with a valve, so that in case it becomes defective, it can readily be cut out without disturbing the flow of water through the others. This transformer, being of very large output, has an efficiency of 98.63 per cent. at full load, 98.2 per cent. at half load, 97.2 per cent. at quarter load, and 98.5 per cent. at one-half overload.

Fig. 23 shows a sectional view of an air-blast transformer of the General Electric type. The construction of the coils *A*, *A* and core *B*, *B* is such that air spaces are left between the parts, and the transformer is mounted over an air chamber in which about ½ ounce air pressure is maintained by motor-driven fans. The air passes through the openings in the core, between the coils, and out at the top and sides; suitable dampers are provided by means of which the flow can be regulated. This makes an efficient and cleanly method of cooling large transformers.

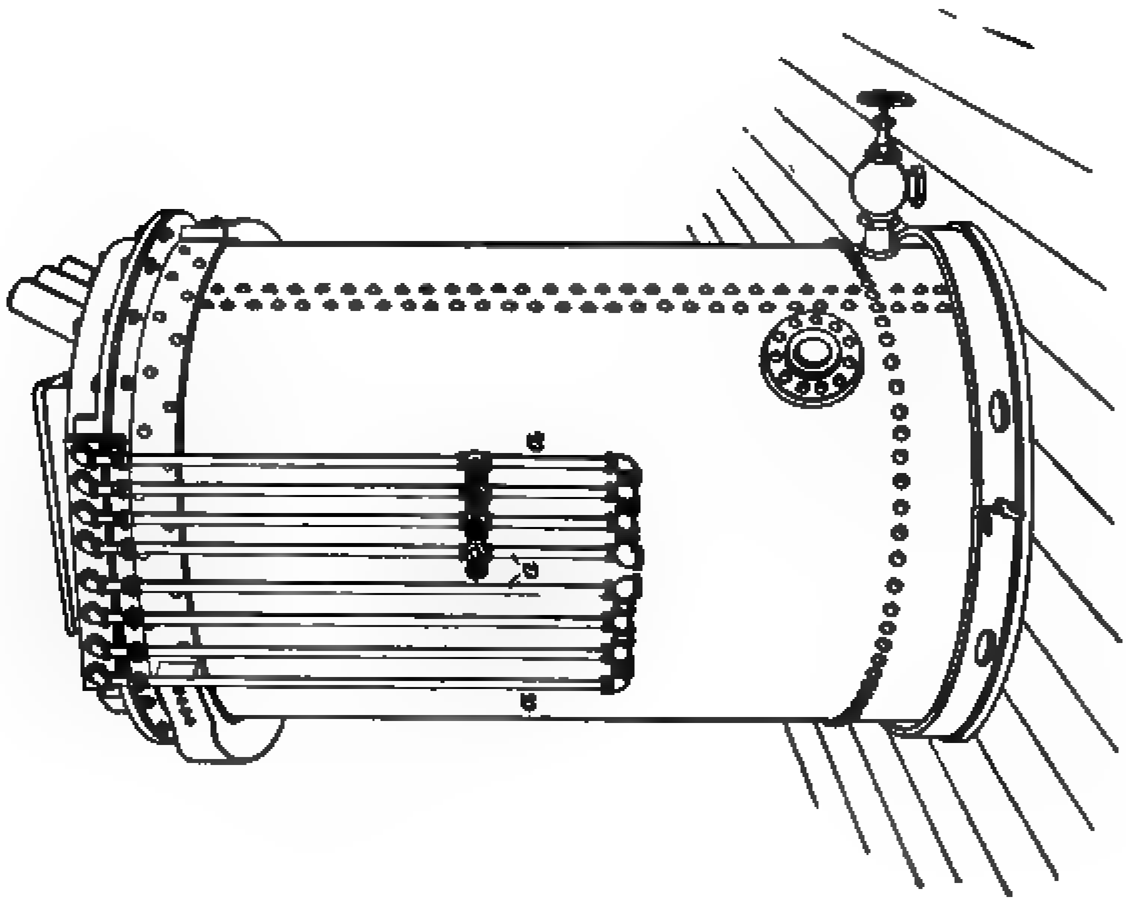


FIG. 22 (b)

FIG. 22 (a)

Fig. 24 shows a group of nine air-blast transformers of 150 kilowatts each. A motor-driven fan is mounted at each end of the chamber and either fan has sufficient capacity to keep the transformers cool, thus providing a reserve blowing outfit in case one breaks down. The power required to operate the fans does not usually exceed one-tenth of 1 per cent. of the transformer output.

23. Polyphase Transformers.—In Europe, two-phase and three-phase transformers have been quite commonly used, and three-phase substation transformers are now manufactured in America. By using polyphase transformers, a saving in material is effected, thus reducing the cost per kilowatt. Also, a considerable saving in space is gained because a polyphase transformer, of given output, takes up less room than an equivalent output in single-phase transformers. This is an important consideration in stations located in large cities. On the other hand, the use of single-phase transformers is somewhat safer, because if a breakdown occurs it is liable to damage but one of the transformers.

Fig. 23

Fig. 25 shows the general arrangement of a three-phase core-type transformer. The primary and secondary coils, which are wound on the cores *A*, *B*, *C*, may be connected Y or Δ. The magnetic flux in the core follows the same changes as the currents. Each core acts alternately as the return path for the flux in the other two cores, just as each

line wire acts alternately as the common return for the other two in a three-phase line. The iron in the core is thus worked

Fig. 24

to better advantage than when three separate single-phase transformers are employed. A two-phase transformer can be made by winding coils on cores *A* and *C* and leaving core *B* without coils; *B* will then act as the return path for the fluxes set up by the coils on *A* and *C*. Since these two fluxes will differ in phase by 90°, the resultant flux in *B* will be $\sqrt{2}$ times the flux in *A* or *C*; hence, for a two-phase transformer, the central core *B* will have a cross-section $\sqrt{2}$ times that of *A* or *C* instead of being equal as shown for the three-phase transformer.

Fig. 25

ROTARY CONVERTERS

24. The main features of **rotary converters** were described in connection with alternating-current apparatus. The types generally used are the two-phase or quarter-phase, three-phase, and six-phase; in America, the three-phase converter is used more largely than either of the others. Each converter is provided with its transformer or set of transformers in case it is necessary to step-down the line voltage. In some stations, notably in railway power plants, the alternating current is generated at low pressure when the

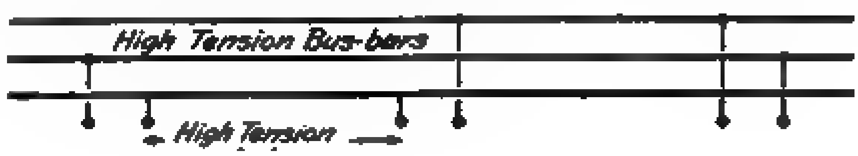


FIG. 26

greater part of the power is used near the station. In such plants, the near-by portions of the system are supplied with direct current from rotary converters placed in the main station and supplied with current directly from the alternators without the intervention of step-down transformers. If a very large percentage of the power was used as direct current for near-by points it would probably be cheaper to install double-current generators and dispense with the converters. In the majority of cases, however, where

converters are used it is necessary to use transformers to supply a suitable voltage.

25. Connections for Six-Phase Rotary Converters. It has been shown that the output of a rotary converter is increased by increasing the number of phases, and six-phase converters are used to a considerable extent, especially where the machines are of large output. Six phases are easily obtained from three by providing each of the three transformers with two secondary coils, as shown in Fig. 26. Coils *1*, *3*, and *5* are connected Δ, as also are *2*, *4*, and *6*, one group being reversed as regards the other, thus giving the double-delta arrangement indicated in Fig. 27. The collector rings are attached to the points *a*, *b*, *c*, etc., thus supplying the converter with six currents differing in phase by 60°. The use of six phases introduces some additional complication in the connections between the transformer secondaries and the converter, and also requires six collector rings, but this extra complication is more than offset by the increased output of the converters. Sometimes switches are inserted between the transformer secondaries and the converter, but more often the switching is done on the primary side because the secondary current is usually large and the switching devices correspondingly heavy.

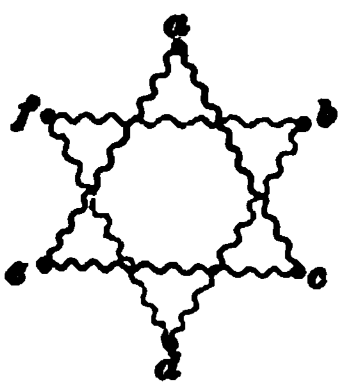


FIG. 27

26. Voltage Regulation of Rotary Converters. Usually it is necessary to arrange converters so that their direct-current voltage can be increased with increase of load so as to keep the voltage constant at distant points on the system. It was pointed out in connection with the theory of rotary converters, that the voltage of the direct-current side could be raised or lowered within certain limits by changing the field excitation of the converter. The change in field excitation with increase in load is usually obtained by providing the machine with a compound field winding similar to that on a compound-wound, direct-current dynamo. If the load were not of a suddenly fluctuating character, the

necessary field regulation could be obtained by adjusting the rheostat in the shunt-field circuit, and a series-field winding would not be needed.

In order to admit of voltage regulation by varying the field strength of the converter, it is necessary to have a certain amount of reactance on the alternating-current side; this can be provided by inserting reactance coils between the transformers and the collector rings, as shown in Fig. 28. *A*, *B*, and *C* are the step-down transformers, and *D* is a laminated core on which the three reactance coils are wound.

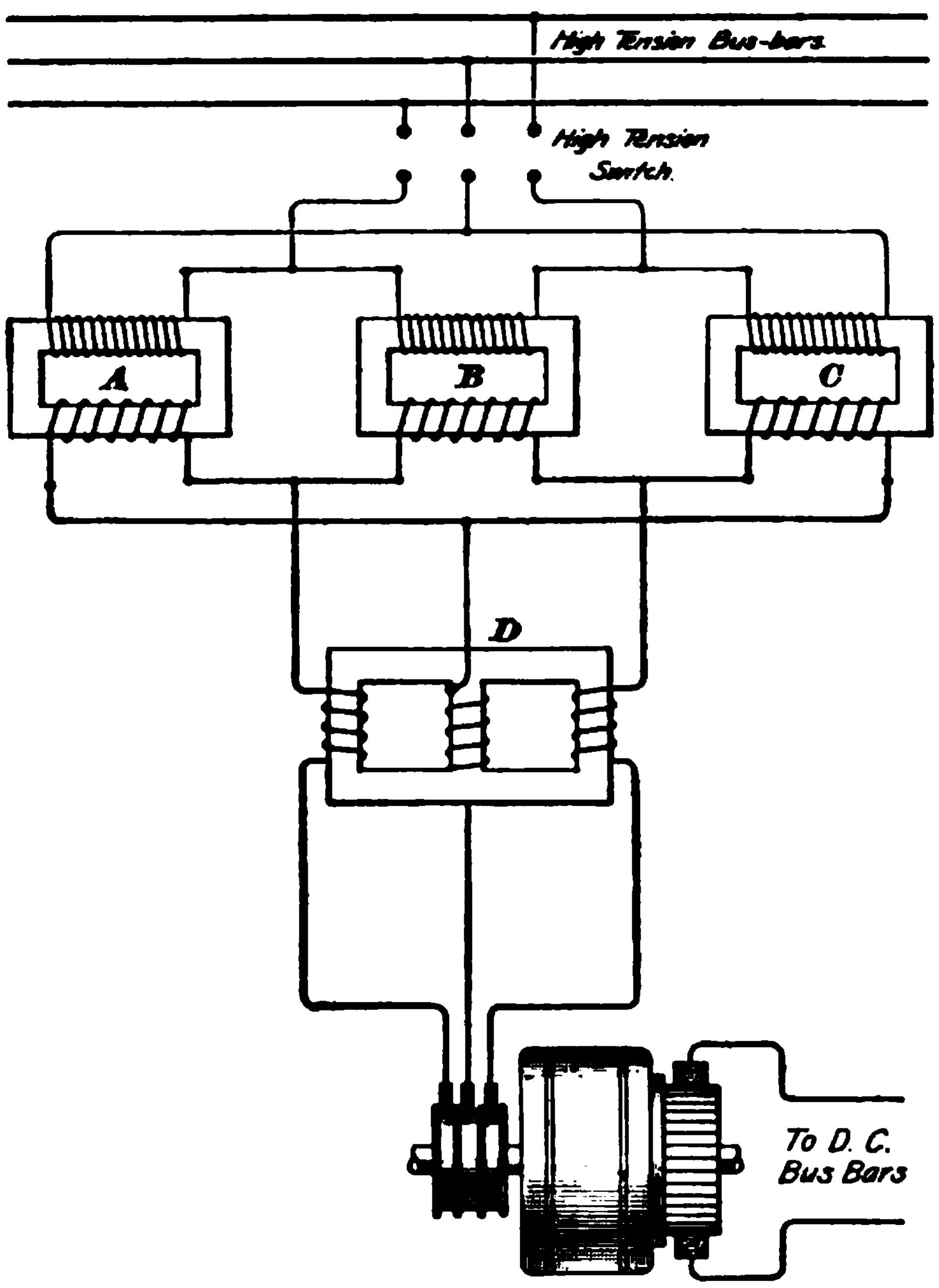


FIG. 28

Another method of regulating the voltage of a converter is to provide the transformer secondaries with a number of taps connected to a multipoint switch, thus allowing the number of secondary turns to be varied. This method does not admit of as gradual a variation in voltage as some others, but it is simple and well adapted to cases where a considerable range in voltage regulation is desired.

A third method of regulation is to insert a *potential regulator* between the transformer secondaries and the collector rings. These regulators are made in a variety of forms, but they are nearly always some special type of transformer; the general features of this method of regulation will be understood by referring to Fig. 29. The secondary coils s, s, s of

the regulator are connected in series with the leads running between the transformers and the converter; the primaries *p*, *p*, *p* are connected across the three phases as shown. Since the secondary coils are in series with the mains, it is evident that their E. M. F.'s will be added to or subtracted from those of the main transformers. If provision is made for varying the value of the E. M. F.'s generated in *s*, *s*, *s*, or for changing their phase relation with respect to the E. M. F.'s of the main transformers, the E. M. F.'s applied to the converter can be raised or lowered by an amount equal to the pressure generated in *s*. In some regulators, the effective E. M. F. of the series-coils is varied by cutting turns in or out, as, for example, in the Stillwell regulator. Provision is also made for reversing the E. M. F. of the coil with respect to the circuit, so that the main E. M. F. can be raised or lowered. Another scheme is to arrange the magnetic circuit or the secondary coil so that by moving the coil or a portion of the core, the amount of magnetic flux passing through the secondary can be varied, thus changing the value of the induced E. M. F.

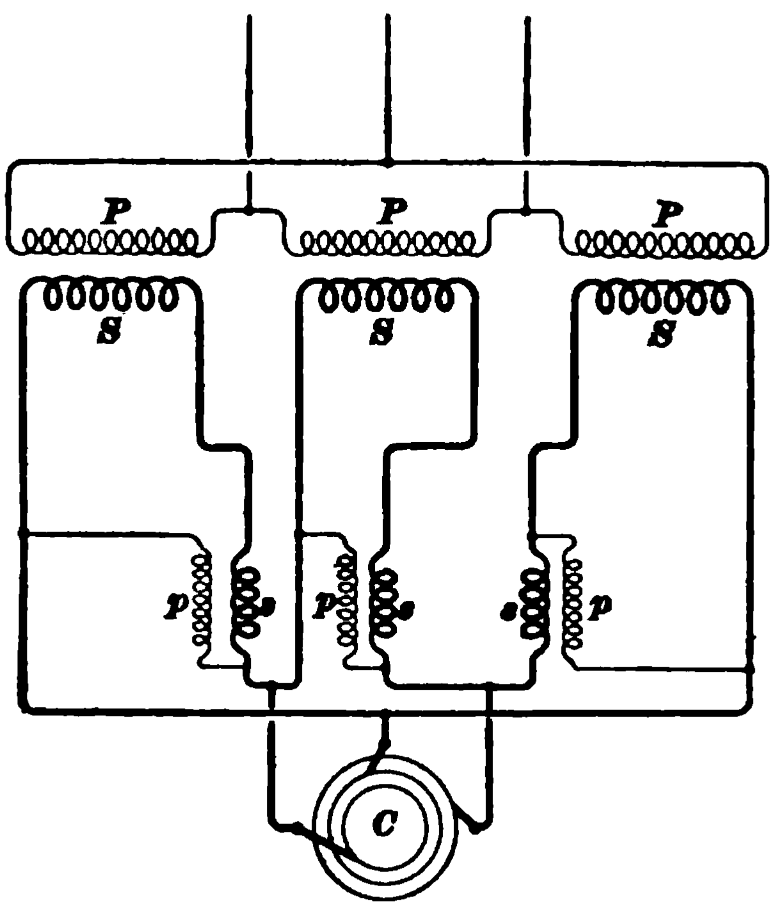


FIG. 29

27. Fig. 30 (*a*) shows the general appearance of a three-phase induction potential regulator made by the General Electric Company and intended for regulating the voltage of a rotary converter. The stationary part of this regulator, Fig. 30 (*b*), consists of a laminated structure *a*, *a* with inwardly projecting teeth exactly similar to the field of an induction motor. This is provided with distributed bar windings *b*, *b*, which are connected in series with the mains

running to the converter. The primary consists of a laminated core *c*, *c* similar to the armature core of an induction motor; this is mounted on a vertical shaft *s* so that the core can be turned through a limited range by means of the hand wheel *h*, which operates a worm engaging with a segmental gear attached to *s*. The primary is provided with three windings distributed in the slots, and connected across the phases as described in connection with Fig. 29. In this type of regulator, the field set up induces an E. M. F. of constant amount in each secondary winding. The adjustment of the amount of "boost" is effected by varying the phase relation of the secondary E. M. F. to that in the primary. For example, if the secondary induced E. M. F. and the primary E. M. F. are in phase, i. e., with the north and south poles of the primary and secondary windings facing each other, the maximum amount of increase in voltage will be obtained. With the secondary E. M. F. exactly opposite in phase to the primary, the E. M. F. will be lowered by an amount equal to the induced E. M. F. For intermediate positions of the primary, intermediate phase relations are obtained and the E. M. F. will be raised or lowered by an amount corresponding to the value of the component of the secondary E. M. F. that is in phase with or in opposition to the line E. M. F. With a regulator wound for four poles, a movement of 90° will give the total range of voltage, and as the movement is not large the current can be conducted into the primary by means of flexible cables. These regulators are also arranged for operation by means of a small motor, thus allowing them to be placed at some distance from the switchboard.

28. **Methods of Starting Rotary Converters.**—In cases where direct current is available, rotary converters are usually started by driving them up to synchronism as direct-current motors. In many substations, storage batteries furnish a source of direct current that is available at all times for starting purposes. Of course, when one converter has been started it can be used as a source of direct current for starting others. In some cases, where a storage battery is

not available, direct current is obtained from a small motor-generator set consisting of an induction motor coupled to a direct-current dynamo. One advantage in starting from the direct-current side is that the direct current furnished by the converter is always of the same polarity, that is, the positive terminal, say, is always positive; whereas, when the converter is brought up to speed by allowing alternating current to flow through the armature, the terminal may be positive at one time, and the next time the converter is started it may show a negative polarity.

When starting from the alternating-current side, the field is unexcited and when the current is first thrown on, the voltmeter connected to the direct-current side will show no

(a)
Fig. 30

(b)
Fig. 30

deflection because the E. M. F. between the direct-current terminals is then rapidly alternating, and, hence, will not effect a voltmeter of the Weston direct current or similar type except perhaps to cause a trembling of the needle. As the converter comes up to speed, the frequency on the direct-current side becomes slower and the voltmeter needle begins to vibrate, its rate of vibration becoming slower as the converter gets more nearly into synchronism. At exact synchronism, the E. M. F. on the direct-current side is steady; hence, the voltmeter reading becomes steady. The field should be excited just before synchronism is attained, and the polarity of the direct-current terminals will depend on which side of the zero the voltmeter pointer happens to be when the field is excited. If the exciting switch is closed with the pointer on the wrong side, the polarity will be wrong.

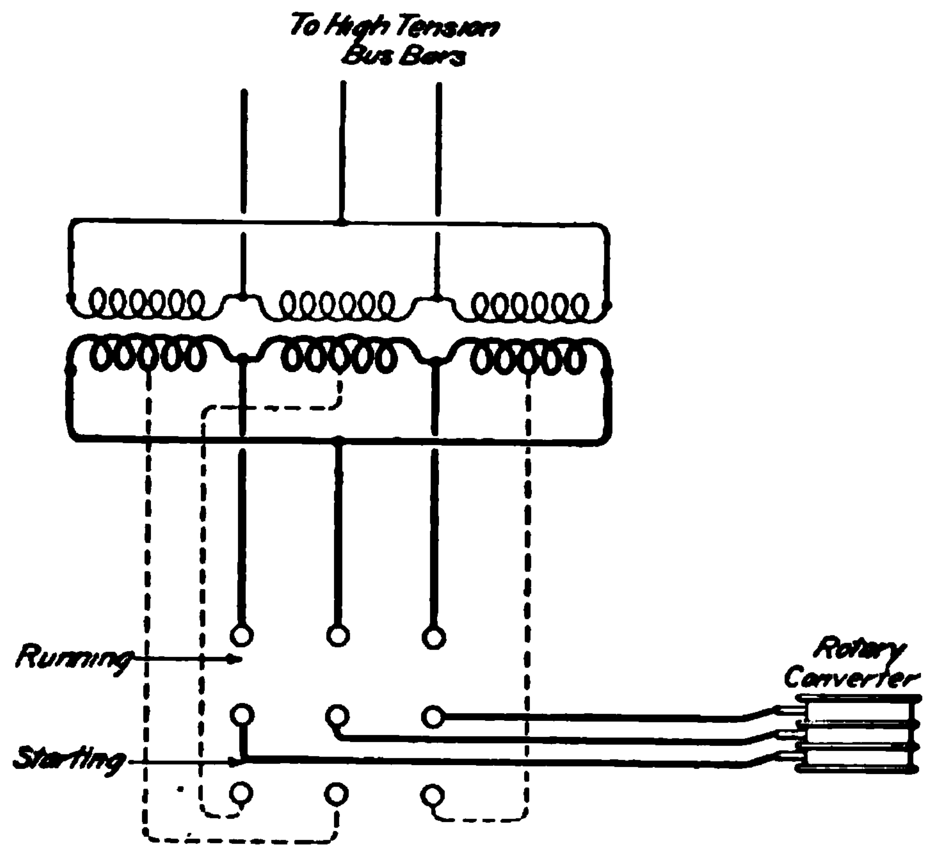


Fig. 31

Another objection to starting with alternating current is that when the current first flows through the armature it sets up an alternating flux through the field coils that may induce extremely high E. M. F.'s in them. Since the field coils are usually connected in series, the total E. M. F. generated may be so high as to endanger the insulation of the coils. When this method of starting is used, it is customary to install a special switch for disconnecting the field coils from each other while the converter is being started. Just before synchronism is attained, the coils are connected in the usual way and supplied with exciting current. It is not usually advisable to apply the full alternating-current voltage to the collector rings until the machine has come up

to speed, because the full voltage will give rise to an objectionable rush of current. To cut down the voltage at starting, a starting compensator similar to that used in connection with induction motors is suitable, but a simpler arrangement is to bring out taps from the transformer secondaries and connect these to a double-throw switch so that in one position of the switch the converter receives half the secondary voltage, while in the running position the full voltage is applied. Fig. 31 shows this arrangement.

One considerable advantage in starting from the alternating-current side is that the converter does not have to be synchronized; it is brought into synchronism by the alternating current. This is an important consideration when a machine must be started in a hurry. Starting from the alternating-current side does not give rise to undue disturbances if the frequency of the converter is fairly low, say 25 cycles per second. On many switchboards connections are provided so that the converters may be started with either direct or alternating current.

FIG. 32

When the converter is started from the direct-current side, it is necessary to insert a resistance in the armature circuit. Fig. 32 shows a type of starting rheostat used for this purpose. On account of the unequal lengths of the switch clips, the three sections of the resistance are successively short-circuited as the switch is closed. As the converter starts up as an unloaded direct-current motor, it comes up to speed quite rapidly and a simple switch giving four or five resistance steps is sufficient.

Where direct current is not available, the converter may be started by means of a small induction motor having its armature mounted on an extension of the shaft. This method is used by the Westinghouse Company. It involves the use of a small auxiliary motor on each converter, and if the station contained many machines it might be cheaper and more satisfactory to install a small motor generator set and start from the direct-current side.

29. Synchronizing Rotary Converters.—Rotary converters and synchronous motors are synchronized with the

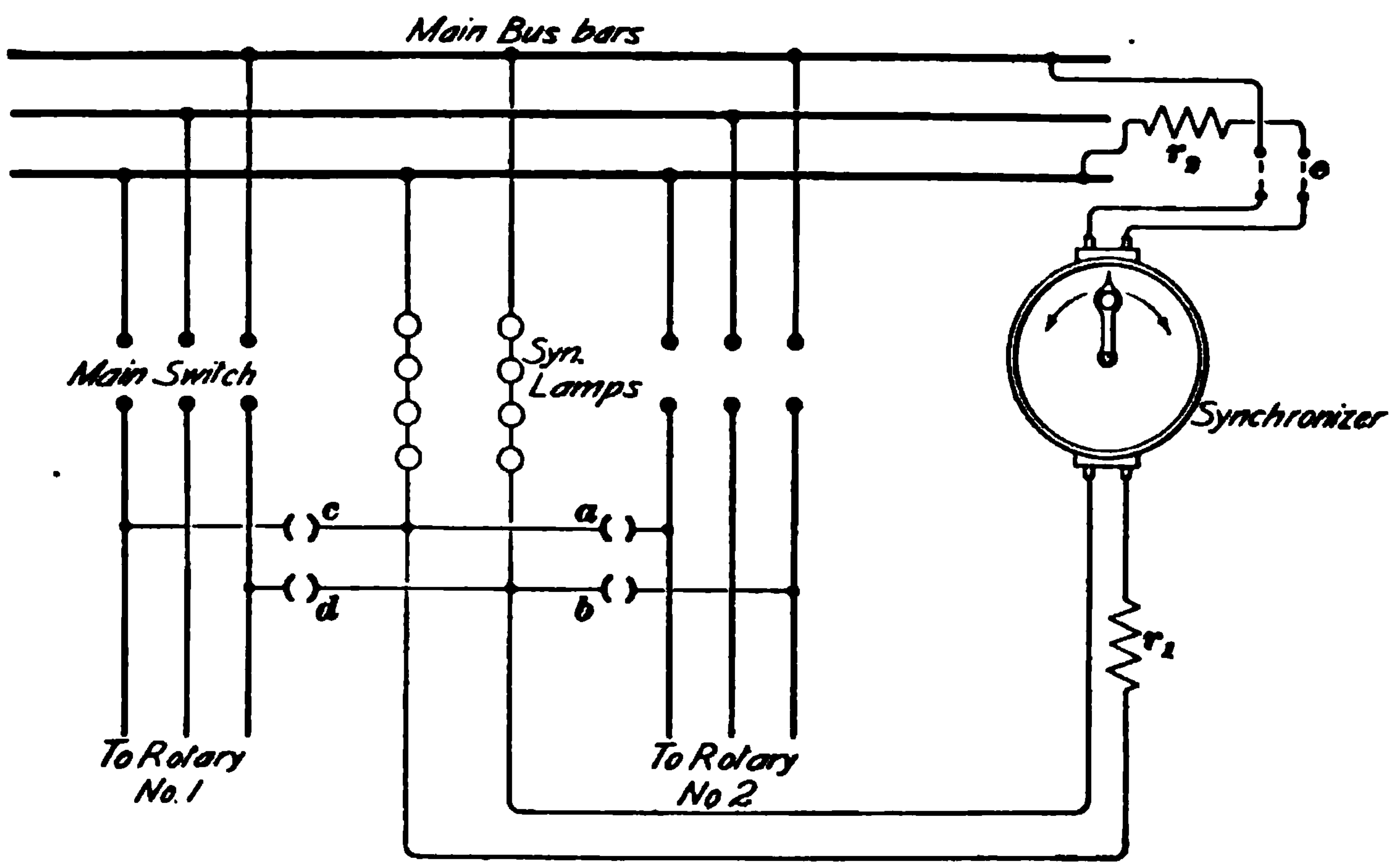


FIG. 33

line E. M. F. in the same way as an alternator is synchronized with the bus-bar E. M. F. Lamps, voltmeters, or synchronoscopes may be used to indicate the point of synchronism. Fig. 33 shows a Lincoln synchronizer used to indicate when either of two rotary converters is in synchronism. In this case the converters are fed directly from low-pressure bus-bars and potential transformers are not needed in connection with the synchronizer. When the pressure is more than 400 or 500 volts, potential transformers should be used. Synchronizing lamps are also provided, enough lamps being connected in series to stand

the voltage. If converter No. 2 were to be synchronized, plugs would be inserted at *a*, *b*, and *e*, thus connecting the upper terminals of the synchronizer to the busbars and the lower terminals to the corresponding phase of the converter. When the synchronizer is used on pressures somewhat above those for which it is made, it is necessary to insert resistances as shown at r_1 and r_2. In new installations, synchronoscopes are now used in preference to lamps.

APPARATUS FOR CONTROLLING THE OUTGOING CURRENT

30. The apparatus for the control of the outgoing current is generally grouped on a switchboard by itself. In most cases the current is delivered at comparatively low pressure; hence, the devices used on the switchboard for the outgoing current differ materially from those on the incoming lines. Generally, the delivered current is used for electric lighting and power, or street-railway purposes, and the switchboard appliances used are the same as if the power were supplied from an ordinary station. Rotary converters are operated in parallel and connected up on the direct-current side in exactly the same way as direct-current machines. If they are compound wound an equalizing connection must be used.

LOCATION AND GENERAL ARRANGEMENT OF SUBSTATIONS

31. One of the greatest advantages of the distribution of power by means of substations is that the substations may be placed at or near the centers where the heaviest demand for current exists. They do not have to be located with reference to coal or water supply, and the price of real estate becomes a comparatively small item, because substations have a very large output compared with the ground space they occupy. They can also be placed in locations

where a power plant would not be permitted on account of the smoke and dirt caused thereby. Substations can, for these reasons, be placed near the center of the load, and thus effect a great saving in the amount of copper required for feeders.

32. Fig. 34 shows the interior of a typical substation, one of the substations in Buffalo, N. Y., supplied with power from the Niagara power plant. All the machinery and controlling devices are here placed in one room, and a

Fig. 34

single attendant is all that is needed. It is a fireproof building provided with a hand-operated overhead traveling crane for handling the machinery during installation, or in case repairs are necessary. The step-down transformers *A*, *A* are ranged along one side, and the three rotary converters *B*, *B*, *B* along the other. Each converter is of 400 kilowatts capacity and is supplied by a group of three 150-kilowatt transformers, the secondaries of which are connected to the converter; air-blast reactance coils, placed

behind the transformers, are inserted between the transformers and the converter in order to permit voltage regulation by variation in field strength. The converters are six-pole machines supplied with 25-cycle current, and run at a speed of 500 revolutions per minute.

The incoming current at 10,000 volts enters in the basement by means of a lead-covered cable and passes through the hand-operated oil switch *C*, which is provided for cutting off all power from the station in case of emergency or for any other reason. From *C*, the current passes through the high-tension circuit-breakers located on the switchboard *D*, and provided with time-limit relays. After passing through the circuit-breakers, the current goes to the high-tension bus-bars *E* and from there to the three high-tension oil switches *F* mounted in a brickwork casing. In the figure, one of the iron covers is removed showing the three cells of one switch. Each switch controls the current in the primaries of a group of three transformers supplying a rotary converter. The potential transformers for supplying current to the voltmeters and synchronizing lamps are shown at *g*, *g* on top of the oil switches. The switchboard for controlling both the incoming and outgoing currents is shown at *H* immediately below the gallery containing the high-tension switches and circuit-breakers. The portion of the switchboard that contains the instruments for the alternating current is at the right-hand end at *K*; three panels are provided, one for each converter and group of three transformers. The switch handles for operating switches *F* are mounted on these panels and are thoroughly insulated, by insulating joints, from the switches themselves. The ammeters are supplied from current transformers, so that none of the appliances on the switchboard with which the operator might come in contact are exposed to the high pressure; all the high-pressure devices are confined to the upper gallery.

From the high-tension switches *F*, the current passes to the primary coils of the transformers and the induced current in the secondaries passes to the collector rings of the

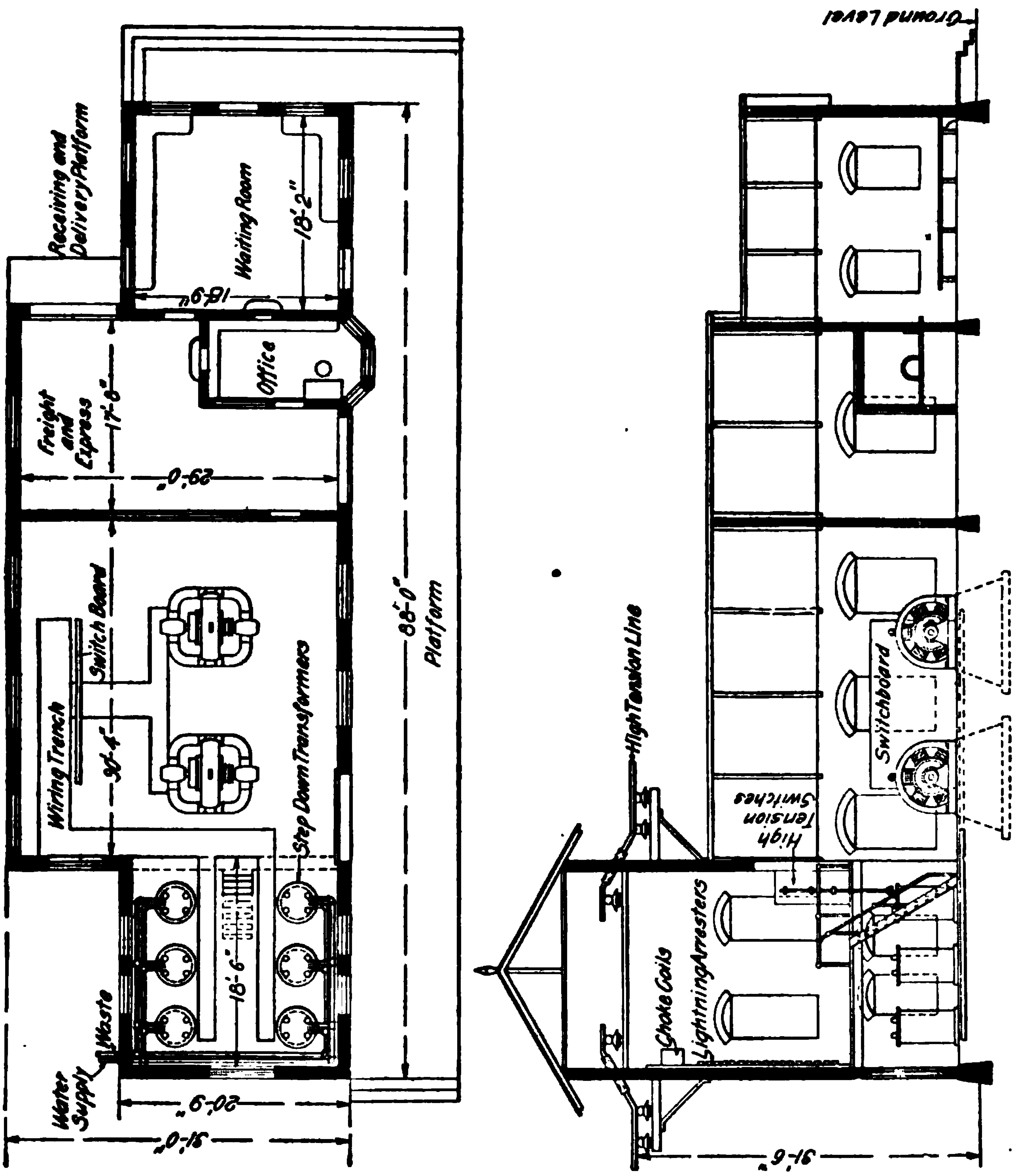

Receiving and Delivery Platform
Waiting Room
18'-2"
18'-9"
Office
Freight and Express
17'-6"
29'-0"
Switch Board
Wiring Trench
30'-4"
Step Down Transformers
18'-6"
88'-0"
Platform
Water Supply
Waste
20'-9"
31'-0"
Ground Level
High Tension Line
High Tension Switches
Switchboard
Choke Coils
Lightning Arresters
31'-6"

FIG. 35

converters. The direct current passes to the panels *1*, *2*, *3*, each of which is provided with a direct-current ammeter and circuit-breaker in addition to the main switches. The outgoing feeders are connected to the feeder panels *4*, *5*, *6*, etc., each of which is provided with an ammeter, circuit-breaker, and main switch. Panel *9* carries an ammeter that measures the combined output of the converters, a voltmeter for measuring the direct-current voltage, and a recording wattmeter for registering the output of the substation. The voltmeter can be connected to any converter by means of plug connections on each converter panel. The subbase of each converter panel carries a single-pole switch for the field, and a double-pole transfer switch for connecting whichever converter is to be started to the starting switch on the subbase of panel *9*. Each converter is provided with an iron-clad magnet *m* mounted on the end of the bearing casing. A current is sent through this magnet at regular intervals, thus making the shaft oscillate back and forth and keeping the brushes from wearing ridges in the commutator. Mechanical devices that have the advantage of not requiring any current for their operation have also been designed for maintaining an oscillation of the shaft.

Fig. 35 shows the arrangement of a typical substation for an electric railway. The arrangement of the transformers, rotary converters, etc. is clearly shown, so that further comment is unnecessary.

CONNECTIONS FOR SUBSTATIONS

33. The connections used for the various appliances in a substation vary considerably in different installations, so that it is impossible to give any scheme that is generally applicable. For example, those for a substation supplying a street-railway system will differ from those for one supplying current for lighting purposes. In order to give an illustration of connections a few typical examples of substations for supplying direct current will be selected. In the first case the substation is to be supplied with current over one or

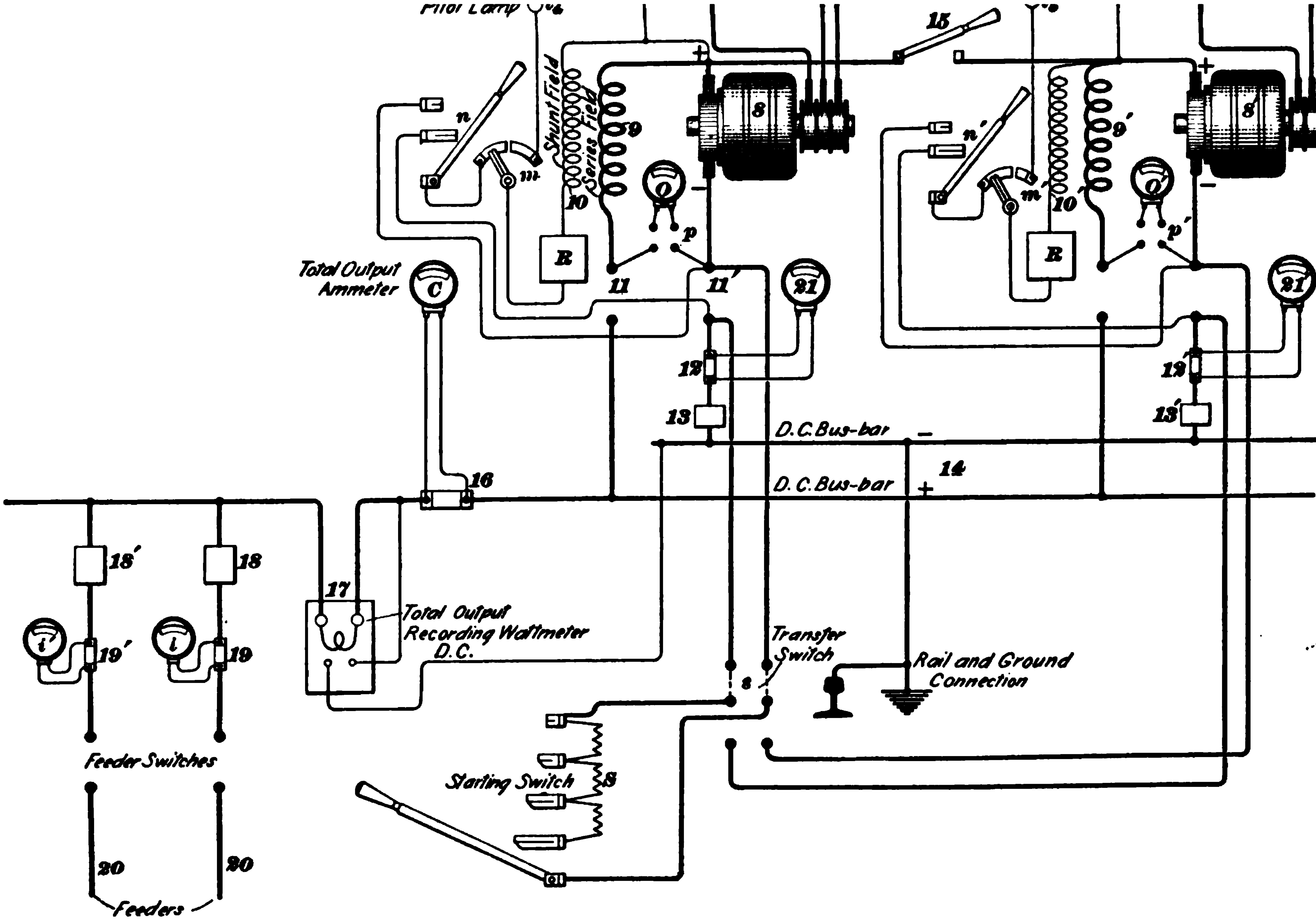

Pilot Lamp
15
Shunt Field
Series Field
n
m
R
10
9
8
O
p
11
11'
+
−
n'
m'
10'
9'
p'
21
12
13
13'
Total Output Ammeter
C
16
D.C. Bus-bar
D.C. Bus-bar
14
18'
18
17
Total Output Recording Wattmeter D.C.
i'
19'
i
19
Transfer Switch
s
Rail and Ground Connection
Feeder Switches
Starting Switch
S
20
20
Feeders

FIG. 36

§ 26

both of a duplicate set of high-tension transmission lines. Two compound-wound rotary converters are used, which are to be arranged for parallel operation. The converters are to be started by means of direct current supplied by either one of the machines, it being assumed that one converter is always in operation. In case both were shut down for any cause, they could be started from the power station by starting up the alternator and bringing the converters and alternator up to speed together. Fig. 36 shows a scheme of connections that might be used for such a substation. It must be understood, however, that the connections in individual cases might differ considerably from those shown, and yet give practically the same results. The differences would not lie so much in the main connections as in those of the auxiliary parts, such as the various instruments, synchronizing devices, etc.

34. Path of Main Current.—The wiring, as a whole, can be divided into two sections; that between the converter *8* and the incoming lines *1*, *2*, and that between the converter and the outgoing feeders *20*, *20*. In the first section the current is alternating, while in the second it is direct. The main current enters on either one or both of the three-phase lines *1*, *2*, and passes to the high-tension bus-bars *3*, *3*. High-tension switches *1′ 2′* are provided to cut off all current from the station. From the bus-bars *3*, *3*, the high-tension current passes to the converters through the switches *4*, *4′*. We will confine our attention from this point to one converter, as the connections of each are exactly alike. After reaching switch *4*, the current passes through the high-tension fuses *5* to the primary coils of the step-down transformers *6*. The switch *4* is frequently provided with an automatic tripping device that will open the circuit in case of overload, in which case the fuses *5* are not needed. In other cases a non-automatic switch is used at *4*, and automatic circuit-breakers instead of fuses at *5*; the transformers *6* step-down the line voltage to an amount suitable for conversion. For example, in this case the

converters will supply a voltage of about 550 for street-railway purposes, and the voltage supplied by the secondaries of *6* will, for a three-phase converter, be $550 \times .612 = 337$ volts, approximately. From *6* the low-pressure alternating current passes through the reactance coils *7*, which are inserted to allow voltage regulation; in case potential regulators are used instead of reactance coils, they are inserted at this point. From *7*, the current passes to the collector rings of the converter *8* and is transformed to direct current at 550 volts. The direct current passes through the main switches *11*, *11'* to the direct-current bus-bars *14*. Since this substation supplies an ordinary street railway operating with an overhead trolley or third rail, the negative bus-bar is connected to the track and ground, while the positive connects to the outgoing feeders, which in turn are attached to the trolley wire or third rail, as the case may be.

35. Connections for Synchronizing.—Each of the incoming lines is provided with a potential transformer t' or t'', and each converter is also provided with a high-tension transformer, such as t''' connected between the switch and the transformer primaries. In series with the secondaries of each transformer is a synchronizing lamp l_1, l_2, etc. Suppose that current is being supplied over line *1* and that converter *8* is to be synchronized. The converter is started, switch *4* being open, by supplying it with direct current. It generates an alternating current that is stepped-up by transformers *6* and supplies the primary of t''' with an alternating E. M. F. By inserting plugs at *a* and *c* the secondaries at t' and t''' are connected in series with each other and with lamps l and l_2. If one plug *c* is cross-connected, as indicated by the dotted lines, the lamps will be bright at synchronism. The synchronizing arrangement is essentially the same as that described in connection with the operation of alternators in parallel.

36. Voltmeter Connections.—In order to obtain a reading of the voltage on either incoming line, a voltmeter *V* is provided. By means of a voltmeter plug, connecting the

upper and lower terminals of either of the receptacles *e*, *f*, the voltmeter can be made to indicate the voltage on either line. The voltage of the high-tension side of either converter can be measured by means of the voltmeter *V'*, which is connected to the voltmeter receptacles *g*, *h*. The voltage of the direct-current side of the converters is indicated by the voltmeters *O*, *O'* connected to the voltmeter receptacles *p*, *p'*. The voltage of a converter can thus be compared with the voltage of the line or direct-current bus-bars to which it is to be connected.

37. Ammeter Connections.—Each converter is provided with an ammeter *I* connected to the secondary of a current transformer inserted between the switch *4* and the transformer primaries. In some cases an ammeter is inserted in each line wire, especially in large installations, though this is not absolutely necessary. In some cases, also, ammeters are placed on the incoming lines, series-transformers, of course, being used so as to thoroughly insulate the instruments from the high-tension line. The direct-current side of each converter is provided with an ammeter *21* connected across a shunt *12*. Ammeter *C* indicates the total direct current, since its shunt is connected in series with the main bus-bar between the converters and the feeders. The feeders are provided with feeder ammeters *i*, *i'* connected across the shunts *19*, *19'*.

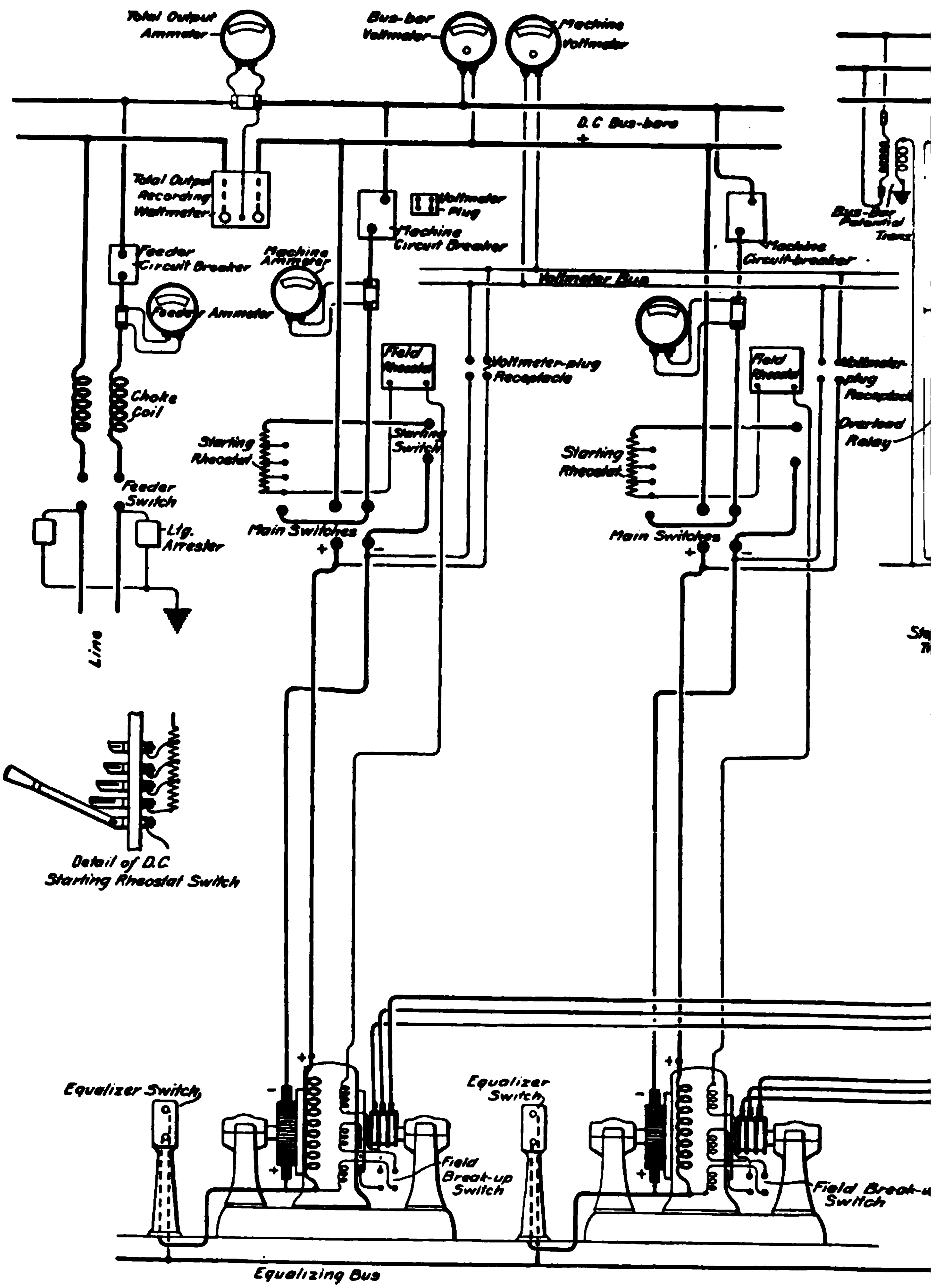
38. Circuit-Breakers.—In this case the incoming lines are not equipped with automatic circuit-breakers, though, if the substation formed part of a large network, circuit-breakers would likely be inserted at *k k'*, and these would be equipped with reverse-current and time-limit attachments. On the direct-current side each converter is provided with a circuit-breaker *13*, *13'* connected between the converter and the direct-current bus-bars. Each feeder is also provided with a circuit-breaker, as indicated at *18*, *18'*.

39. Equalizer Connection.—The positive brushes of the converters are connected by means of an equalizer cable in which the equalizer switch *15* is inserted. Note that

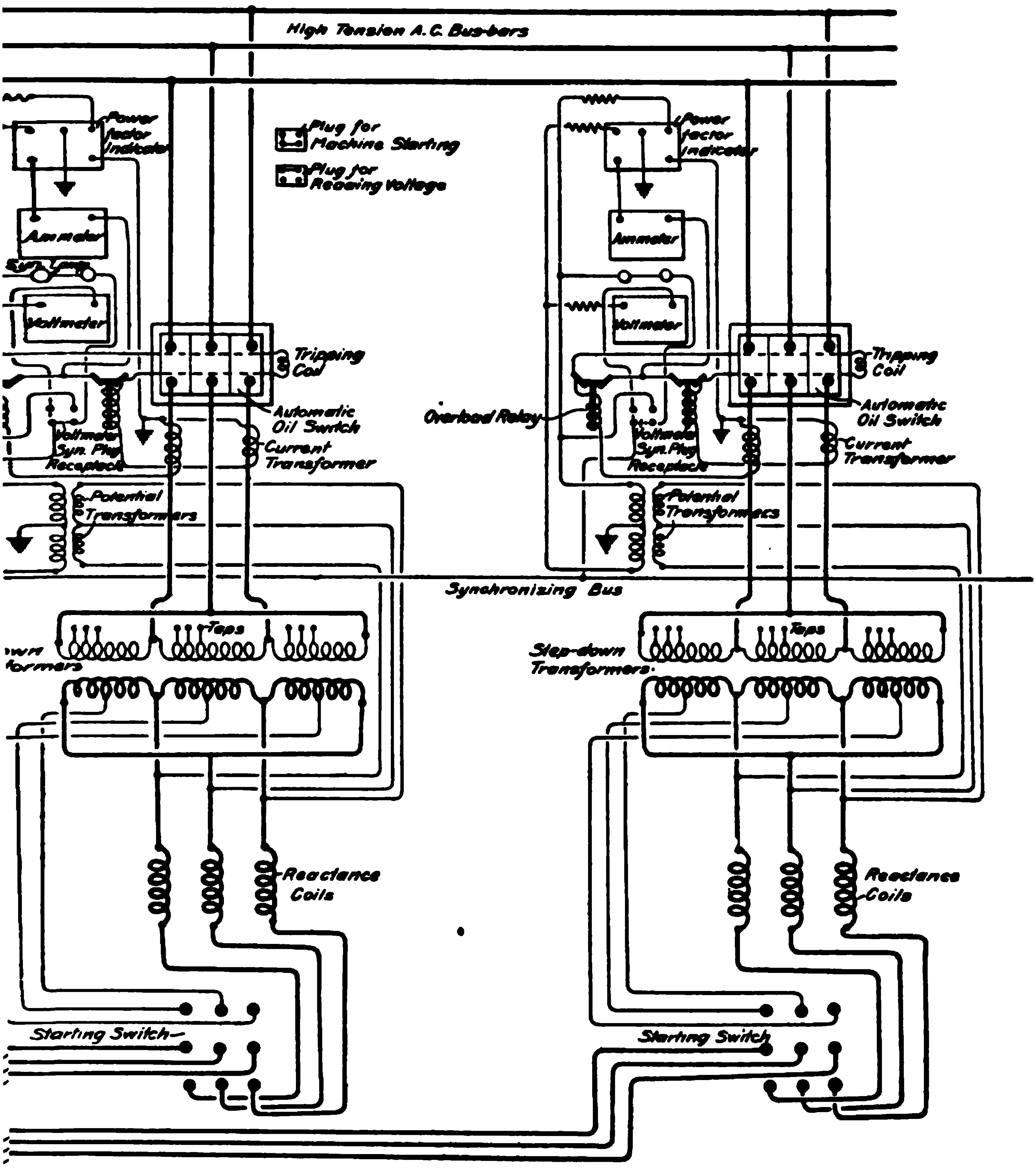
the equalizer connects the two brushes to which the series-field windings are attached.

40. Shunt-Field Connections.—One end of the shunt field connects to the + brush, and the other to one terminal of the field rheostat *R*. The other rheostat terminal connects to the blade of the field switch *m*. When switch *m* is moved to the right, thus cutting the current off from the shunt field, the pilot lamp l_4, resistance *r*, and rheostat *R* are connected across the field terminals, thus allowing the induced E. M. F., caused by the interruption of the field current, to discharge through this closed circuit. Switch *m* is in the position shown in the figure when the converter is in operation. Switch *n* allows the shunt field to be excited either from the direct-current bus-bars or from the converter itself. When it is partly closed, the blade makes contact with the long clip and the field is excited from the bus-bars; when fully closed, the field is connected across the brushes.

41. Method of Starting.—Suppose converter *8'* is in operation supplying current to the direct-current bus-bars, and that *8* is to be started and thrown in parallel with *8'*. Switches *4*, *11*, *11'*, *15*, *n*, and *m* are supposed to be open. Close the equalizer switch *15*; place field switch *m* in the position shown in the figure, and close switch *n* until the blade makes contact with the long clip. The shunt field will then be excited by current from *8'*, because one end of the field is connected through *R*, *m*, and *n* to the negative bus-bar, and the other end is connected to the positive side of *8'* through the equalizer. Close switch *11*, thus allowing current to flow through the series-coils *9*. The field is now fully excited and the converter can be started as a direct-current motor by allowing current to flow through its armature. This is done by throwing the switch *s* to the upper position and gradually closing the starting switch *S*. The speed of *8* can be adjusted by moving the field rheostat *R*, and when the point of synchronism is attained, as indicated by the synchronizing lamps, switch *4* is closed. After *S* has



Total Output Ammeter
Bus-bar Voltmeter
Machine Voltmeter
D.C Bus-bars
Total Output Recording Wattmeter
Voltmeter Plug
Machine Circuit Breaker
Feeder Circuit Breaker
Machine Ammeter
Feeder Ammeter
Voltmeter Bus
Machine Circuit-breaker
Bus-Bar Potential Trans
Field Rheostat
Voltmeter-plug Receptacle
Choke Coil
Starting Rheostat
Starting Switch
Overload Relay
Feeder Switch
Main Switches
Lig. Arrester
Line
Detail of D.C. Starting Rheostat Switch
Equalizer Switch
Field Break-up Switch
Equalizing Bus



High Tension A.C. Bus-bars
Power factor Indicator
Plug for Machine Starting
Plug for Receiving Voltage
Ammeter
Syn. Lamp
Voltmeter
Tripping Coil
Automatic Oil Switch
Overload Relay
Voltmeter Syn. Plug Receptacle
Current Transformer
Potential Transformers
Synchronizing Bus
Taps
Step-down Transformers
Reactance Coils
Starting Switch

been closed and the resistance cut out, switch *11'* should be closed and switches *S*, *s* opened; also, *n* should be fully closed, thus connecting the shunt field across the terminals of the converter and allowing the field to remain excited even if switches *11*, *11'*, and *15* are open. The transfer switch *s* is provided so that the starting rheostat *S* can be connected to either converter.

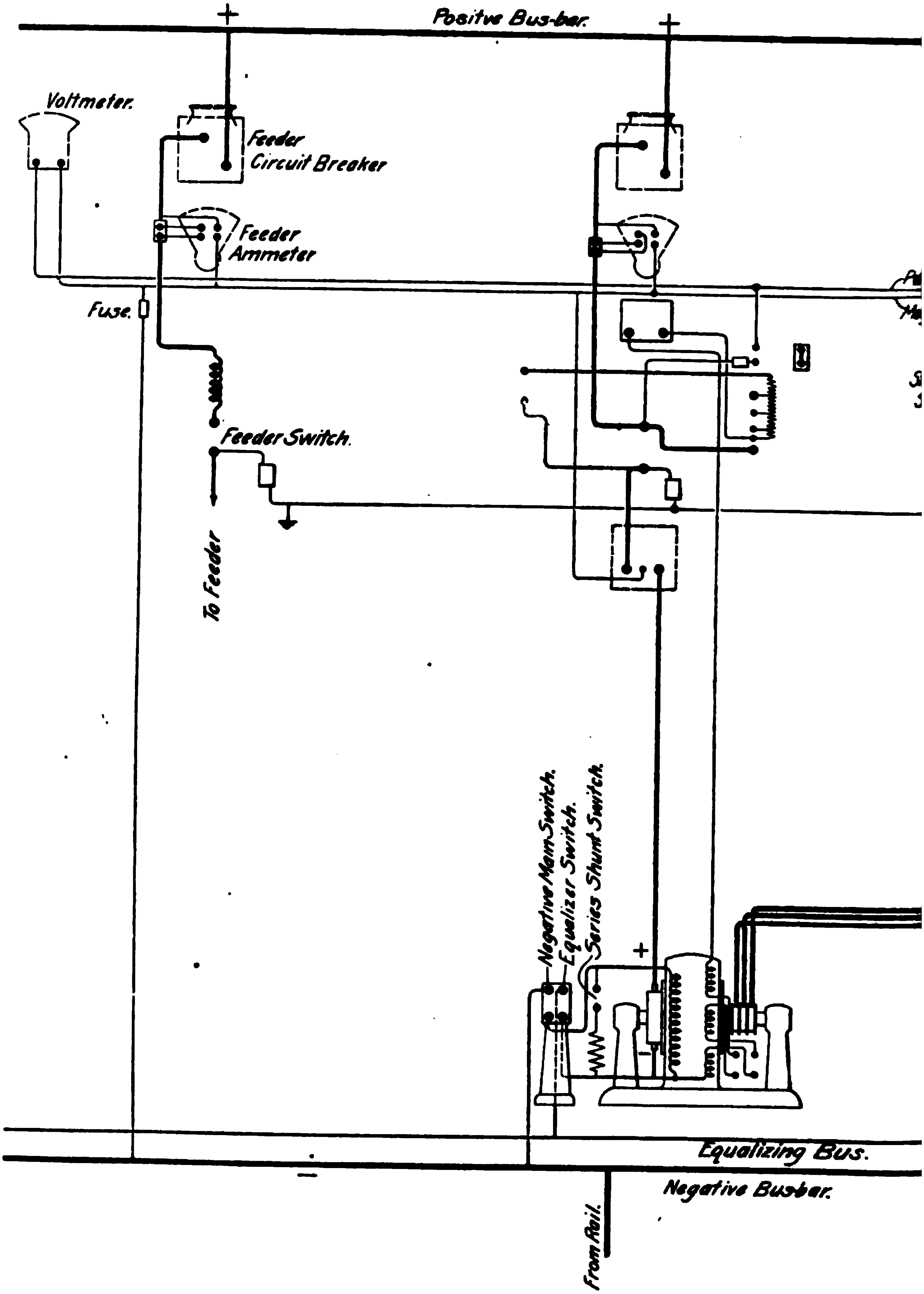
This method of starting from the direct-current side is sometimes modified as follows: The converter is speeded up as before and the field rheostat is adjusted so that the machine runs somewhat above synchronism. Then switches *11*, *11'*, and *n* are opened, thus cutting off the direct current and opening the field circuit. The converter is then running above synchronism under its own momentum, but is generating no E. M. F. Switch *4* is then closed and the converter is brought into synchronism by the alternating current, and as it is already running at nearly synchronous speed the amount of current required is not nearly as great as if the converter were started from rest by allowing alternating current to flow through the armature. The field circuit is then closed, the direct-current voltage adjusted, and the converter thrown in parallel on the direct-current side in the usual manner. This method of starting is sometimes advantageous when the load on the direct-current bus-bars is of a very fluctuating nature. The variations in voltage may under such circumstances make it difficult to synchronize with the lamps in the ordinary way.

In case the converters are started by means of an auxiliary induction motor mounted on the shaft, switches *S*, *s* are omitted and the necessary connections for the starting motor are provided instead.

42. Fig. 37 shows connections for a substation containing two rotary converters supplying current to a two-wire lighting or power system. The connections are, on the whole, very similar to those just described but differ from them in minor details. The switchboard is divided into two parts—the alternating-current board at the right and the

direct-current board at the left. The alternating-current board consists of two panels, each of which is equipped with a main switch, which may be located some distance from the panel but yet be operated therefrom; a voltmeter, ammeter, power-factor indicator, overload relays, synchronizing lamps, synchronizing plug, and potential, and current transformers. Each direct-current panel is equipped with two single-pole main switches, field rheostat, machine ammeter, circuit-breaker, voltmeter plug, and starting switch for starting from the direct-current side. Each feeder panel, of which one is shown in the figure, is equipped with a double-pole feeder switch, feeder ammeter, circuit-breaker, and lightning arrester. In addition to the instruments on the generator and feeder panels, a total output ammeter and a total output recording wattmeter are connected between the converters and feeders so as to measure the combined output of the machines. Also, two voltmeters are provided—one to indicate the bus-bar voltage and the other to indicate the voltage of the direct-current side of either converter. These instruments, together with the total output meters, are often mounted on a panel by themselves.

It will be noted in Fig. 37 that the connections are such that the converters can be started from either side. Each machine is provided with a double-throw starting switch on the alternating-current side by means of which the converter is supplied with a reduced voltage at starting. The primaries of the transformers are provided with a number of taps to adapt them to different line voltages, and reactance coils are inserted between the secondaries and the collector rings. The main switch is provided with an automatic tripping attachment that is operated by the overload relays. The synchronizing connections are such that either the synchronizing lamps or voltmeter may be used. Each converter is equipped with a power-factor indicator, which shows whether the current taken from the bus-bars is lagging or leading. The operation of this type of power-factor indicator will be explained later after polyphase meters have been taken up.



Positive Bus-bar.
Voltmeter.
Feeder
Circuit Breaker
Feeder
Ammeter
Fuse.
Feeder Switch.
To Feeder
Negative Main Switch.
Equalizer Switch.
Series Shunt Switch.
Equalizing Bus.
Negative Busbar.
From Rail.

'her
w/.

43. The method of starting from the direct-current side is briefly as follows: On the alternating-current side, the starting switch is thrown to the lower position and the main oil switch is open. The field break-up switch and the equalizer switch at the machine are also closed. The break-up switch is used only when the converter is started from the alternating-current side. The + main switch, the circuit-breaker, and the single-pole starting switch are then closed, first making sure that the starting rheostat switch is open. Closing the + main switch and the equalizer switch places the series-coils in parallel with the series-coils of the converter that is already in operation and also connects one end of the shunt-field winding to the + side of the system. As soon as the starting rheostat switch is placed on the first point, current flows through the armature and shunt field. The converter then starts as a direct-current motor and comes up to speed as the starting rheostat switch is pushed in. After this switch has been fully closed, the – main switch is closed and the rheostat switch opened. The converter is now synchronized by varying the field strength, and when the lamps or voltmeter indicate synchronism the oil switch is closed.

When a converter is started from the alternating-current side, the switches on the direct-current side are open and the field break-up switch is also open. The double-throw starting switch is thrown to the upper position and the main oil switch closed. When the machine has attained speed, the starting switch is thrown over to the full-voltage position. The field is then excited and, after making sure that the polarity of the direct-current side is correct as indicated by the direct-current voltmeter, the converter is thrown in parallel on the direct-current bus-bars.

44. Fig. 38 is a diagram of connections similar to Fig. 37 except that, since the direct current is delivered to a railway system, the arrangement of the apparatus on the direct-current side is different. The connections on the alternating-current side are shown for one converter only; they are the

same as in Fig. 37. The negative bus-bar is placed near tbe machines instead of on the direct-current switchboard, and the negative main switch is placed alongside the equalizer switch, the converters being equalized on the negative side. The negative bus-bar is connected directly to the rail or return circuit, so that the direct-current panels are single-pole and the connections thereby simplified. The arrangement shown in Fig. 38 is used by the General Electric Company and the direct-current ammeters are of the Thomson astatic type, in which the magnetic field is supplied by electromagnets excited from the bus-bars. Each ammeter has a pair of wires to supply the exciting current in addition to the usual pair connecting to the ammeter shunt. The series-field of each converter is provided with a shunt to regulate the amount of compounding; this shunt can be cut out by means of the switch shown in the figure. This is necessary when starting from the alternating-current side; otherwise, the alternating E. M. F. induced in the series-coils would set up a large current through the shunt. These diagrams give a general idea of the connections used for substations, but it must be remembered that they admit of considerable variation and must be adapted to the requirements of each particular case. It is not possible therefore to lay down any general scheme that is applicable to all cases.

MEASUREMENT OF POWER ON POLY-PHASE CIRCUITS

INSTRUMENTS USED FOR POWER MEASUREMENT

45. Reference has already been made, in connection with alternating currents, to the measurement of power on alternating-current circuits. The measurements there described related to simple single-phase circuits; the influence of the power factor on the actual power delivered was pointed out, and the use of the wattmeter was explained. As the applications of polyphase currents to power transmission have now been described, it will be advisable to consider the methods available for measuring the power supplied to two-phase and three-phase systems.

46. On account of the fact that the power factor of alternating-current circuits, either single-phase or polyphase, is seldom 100 per cent. or unity, power measurements are seldom made with ammeters and voltmeters as in direct-current work. The three ammeter and three voltmeter methods are inconvenient, liable to considerable error, and are never used if wattmeters are available. Good portable wattmeters are now obtainable at a price but little greater than that of ammeters or voltmeters. The wattmeter does not indicate the product of the volts and amperes, but the product, volts $\times$ amperes $\times \cos \phi$, where $\cos \phi$ is the power factor.

In making practical power measurements we may wish to obtain simply a reading of the total watts supplied at any given time or we may wish to obtain the total work done, in watt-hours or kilowatt-hours, during a certain period of time. In the first case, indicating wattmeters would be used to make the measurements, while in the second it would be necessary to use recording wattmeters, or watt-hour meters, as they should more properly be called.

INDICATING WATTMETERS

47. The **indicating wattmeters** used for power measurement on polyphase circuits are in nowise different from those already described for use on single-phase circuits. Many reliable makes of portable wattmeters are now available and these are used for commercial measurements. The number of wattmeters required for a given test depends on the conditions under which the test is made. In some cases one wattmeter is sufficient; in others, two are necessary, as will be shown. In connection with polyphase measurements, it is well to bear in mind the fact that if the difference in phase between the currents in the two coils of a Siemens type of wattmeter becomes more than 90°, the twisting action on the movable coil reverses, and, hence the deflection reverses. In ordinary single-phase circuits this condition does not arise, but it is possible in certain cases to have a greater phase difference than 90° on three-phase circuits, and the negative deflection referred to above must be taken into account.

RECORDING WATTMETERS

48. The **Thomson recording wattmeter** has been described; it operates on either direct or alternating current and can be used for measurements on polyphase or single-phase circuits. Meters of the induction type, having no commutator, are simpler in construction than the commutator meter, and have rapidly come into favor. They, of course, have the disadvantage that they cannot be used on direct current, whereas the Thomson meter can be used on either direct or alternating, a considerable advantage where a company supplies both kinds of current. Also, induction meters must be used on circuits having the frequency for which they are adjusted; if used on circuits of other frequency their indications will be incorrect.

49. **Induction wattmeters** are made in many different forms, but they all operate on about the same principle.

They are essentially small induction motors designed to operate with single-phase or polyphase current. Figs. 39 and 40 illustrate the operation of this class of recording meter, though it will be understood that it is possible to have a different arrangement of the parts and yet have the meter operate equally well. In Fig. 39, *a* is a coil of fine wire wound on the laminated iron core *b*; *c*, *c* are coils of a few turns wound on a core *d*, which is entirely separate from *b*. An aluminum disk *e* is mounted on the shaft *f* so that the outer part of the disk revolves past the ends of the cores on which the coils are wound. Fig. 40 shows a section of the coils and core taken along the line *fg*. Coils *c*, *c* are connected in series with each other and with the circuit so that all the current supplied passes through them. The potential coil *a* is connected across the circuit so that the current in it is proportional to the voltage; *c* and *a* therefore correspond to the current and potential coils of an ordinary wattmeter. The magnetism set up in core *b* will be proportional to the voltage, and that set up in core *d* will be proportional to the current. Coil *a* has a high inductance and an additional inductance is usually connected in series with it; in any event,

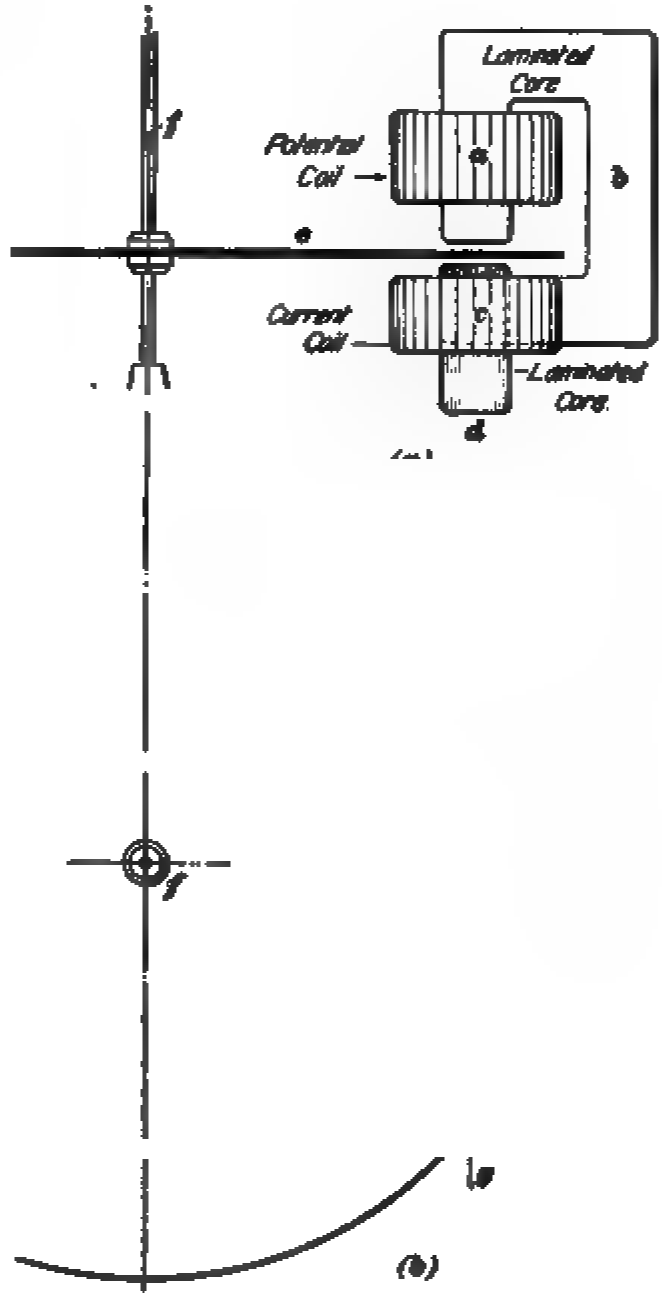


FIG. 39

the meter is so designed that the current in coil *a* will lag approximately 90° behind the E. M. F., thus making the magnetism in *b* lag 90° behind the E. M. F. The current in coils *c*, *c* is, of course, in phase with the current supplied to the circuit in which the meter is connected. The alternating magnetic field set up, say, by coil *a* induces eddy currents in the disk, which spread out somewhat as indicated by the dotted lines *o*, Fig. 39 (*b*). These currents are reacted on by the field that emanates from the poles of core *d* and the disk is made to rotate.

In order that the meter shall give an accurate indication of the work done in the circuit, the driving torque on the disk must be proportional to $EI \cos \phi$, where $\cos \phi$ is the power factor of the circuit. Let us first consider the case where the power factor is 1, i. e., where the line current and line E. M. F. are in phase. The current in *a* is at right angles to the line E. M. F. and the induced eddy currents in the disk are at right angles to the magnetic flux, because these currents depend on the rate of change of the flux, and the flux is changing most rapidly when the magnetizing current is passing through zero. The magnetism in *d* is in phase with the current; hence, for the power factor of 1, the currents in the disk are in phase with the magnetism set up by the series-coils; consequently, the driving torque is a maximum for the given values of the line current and E. M. F. Suppose that we have the same current and E. M. F. but that the power factor is less than 1. The line current will lag behind the E. M. F., the magnetism in *d* will not reach its maximum at the same instant as the currents in the disk, and the driving torque will be reduced, thus making the meter run slower. A magnetic brake is provided by making the disk revolve between the poles of permanent magnets in the same manner as in the Thomson meter. This makes the speed at

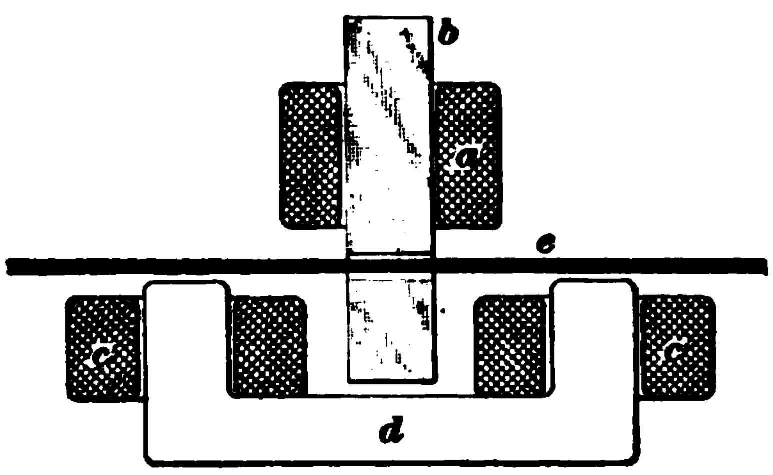


Fig. 40

all times proportional to the driving torque. If it were possible for the circuit to have a power factor of zero, i. e., if the line current lagged 90° behind the E. M. F., the torque action on the disk would be zero, because the induced currents would be at right angles to the magnetism in *d*. In other words, when the currents in the disk were a maximum there would be no field for them to react on, and when the field magnetism was at its maximum there would be no currents in the disk. The meter would not therefore record any power even though current would be flowing in coils *a*, *c*. This is

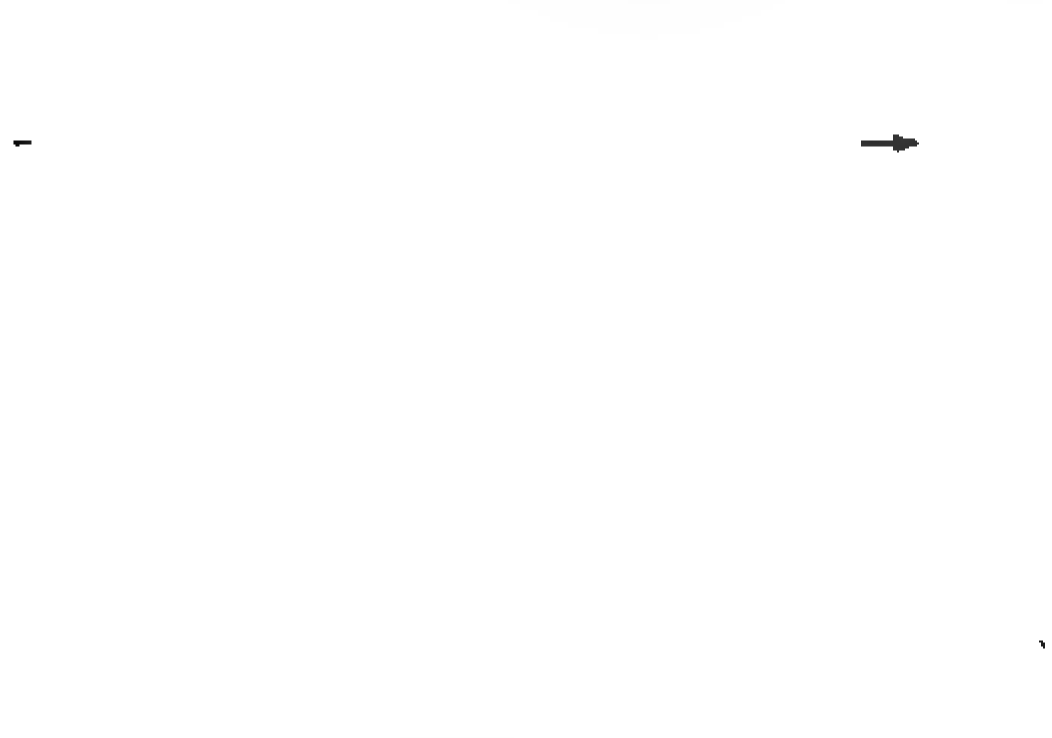


FIG. 41

as it should be, because with zero power factor, the watts supplied would be zero no matter what the values of the current and E. M. F. might be. The induction meter can therefore be made to record the number of true watts expended in a circuit no matter what value the power factor may have.

50. Fort Wayne Induction Wattmeter.—Fig. 41 shows a Fort Wayne single-phase induction wattmeter. *D* is the armature, which, in this meter, takes the form of an inverted aluminum cup. *E* is the damping magnet that exerts a drag on the armature and makes its speed proportional to the driving torque. The current and potential

coils are at the back of the armature; *a* is one current coil, and the other coil occupies a similar position on the opposite side of the armature. The speed of the meter can be adjusted by shifting the magnet *E* up or down, thus varying the amount of the armature embraced by the pole pieces of the permanent magnet.

51. Stanley Induction Wattmeter.—In the Stanley recording wattmeter the armature is an aluminum disk acted on by current and potential coils in much the same manner as previously described. The most interesting feature of this meter is the method of suspending the disk. Instead of resting on a pivot, as in most meters, the disk *a*, Fig. 42, is suspended magnetically. It is mounted on a small, hollow, steel shaft *b* through which passes a fine steel wire *c* stretched taut by means of the screw *d* and spring *e*. The shaft *b* has in it two small brass bushings, one at each end, that bear against the wire and keep the disk from tipping sidewise, otherwise the disk has no support. A permanent magnet *f* is provided with pole pieces *g*, *h* shaped as shown; *k* is a brass plug. From the way in which the pole pieces are shaped the lines of force passing across the gap at *l* hold the shaft in a central position between the poles so that the shaft and disk are magnetically suspended and revolve with very little friction. The reduction in the friction makes the meter more accurate, particularly on light loads, and there is no pivot to be damaged by shock or vibration. The recording dial is operated by gears driven from the shaft by the teeth shown at *m*,

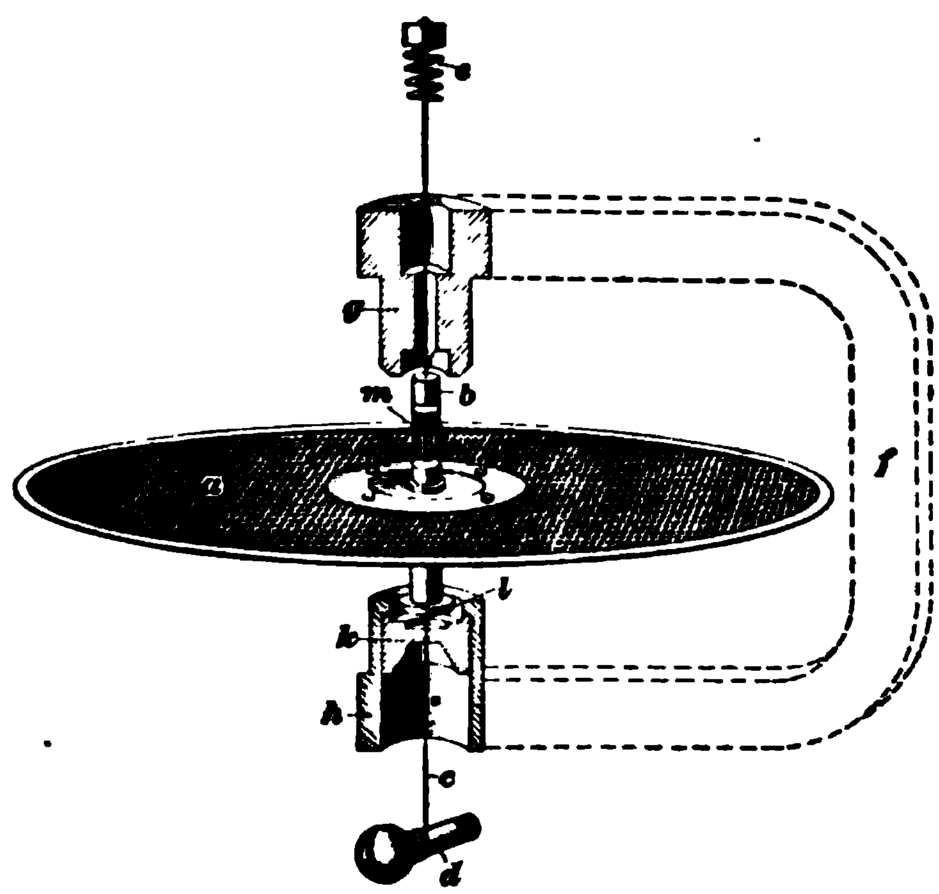


FIG. 42

MEASUREMENT OF POWER ON TWO-PHASE CIRCUITS

52. In making power measurements on polyphase circuits, the methods used will depend, to some extent, on whether the load on the system is balanced or not. The load in such a system is said to be *balanced* when the current in each of the phases is alike, and the power factor of the load on each phase also alike. In other words, the loads on the different phases of a balanced system are alike in every particular; under such circumstances it would be accurate enough to simply measure the power delivered to one phase and multiply the result by the number of phases. Unfortunately, an exact balance is seldom realized in practice,

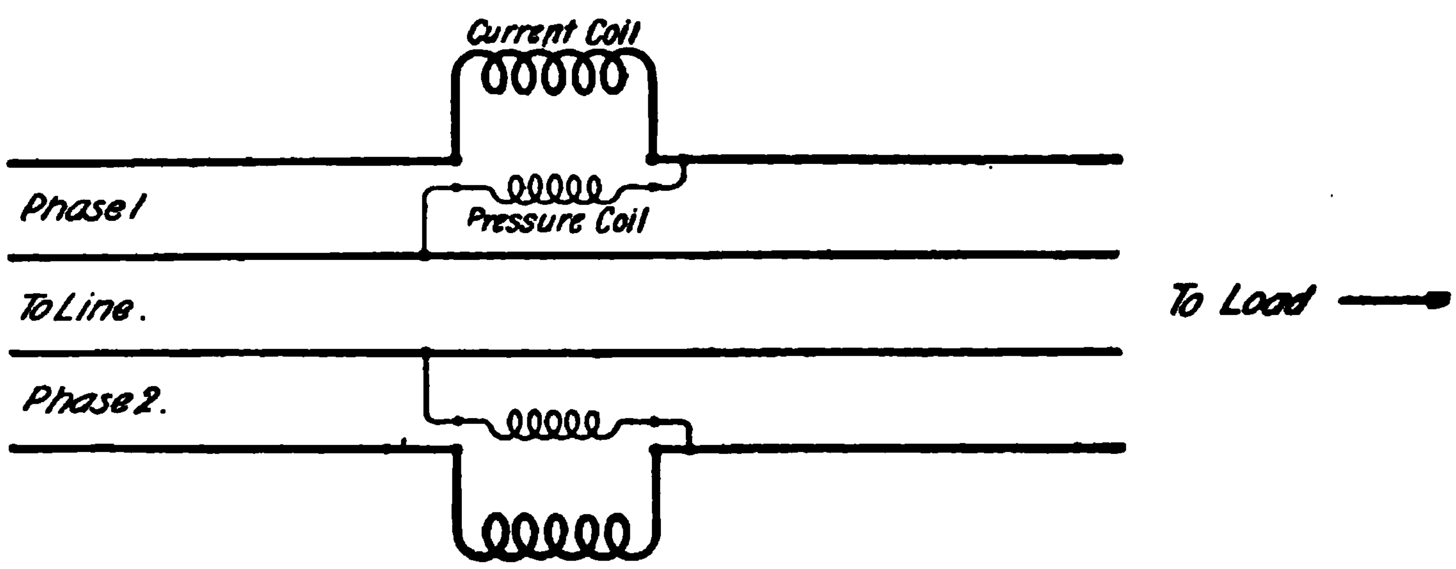


FIG. 43

although induction motors, synchronous motors, and rotary converters in themselves constitute a nearly balanced load, because they take current from the different phases in practically equal amounts. When a mixed load of lights and motors is operated, it is almost impossible to obtain an exact balance.

53. Two-Phase, Four-Wire System.—Fig. 43 shows the usual method of connecting wattmeters for measuring power on a two-phase, four-wire system. Each phase is provided with a wattmeter, there being a current coil in each phase; the pressure coils are connected across the phases. In series with the pressure coil there would be a resistance, as in all wattmeters of the electrodynamometer type; this

resistance is not shown in the accompanying figures, and the fine-wire coil can be taken to represent the complete potential circuit of the wattmeter including the usual protective resistance.

Fig. 43 shows two distinct circuits containing wattmeters. It is evident that the sum of the two readings will give the total power supplied to the motor or other devices to which the lines are connected. Also, the sum of the readings will give the power supplied whether the load is unbalanced or not, because each wattmeter measures the actual number of watts supplied to the phase in which it is connected. Fig. 44 shows the two wattmeters used on a two-phase system with a common return. Recording wattmeters of

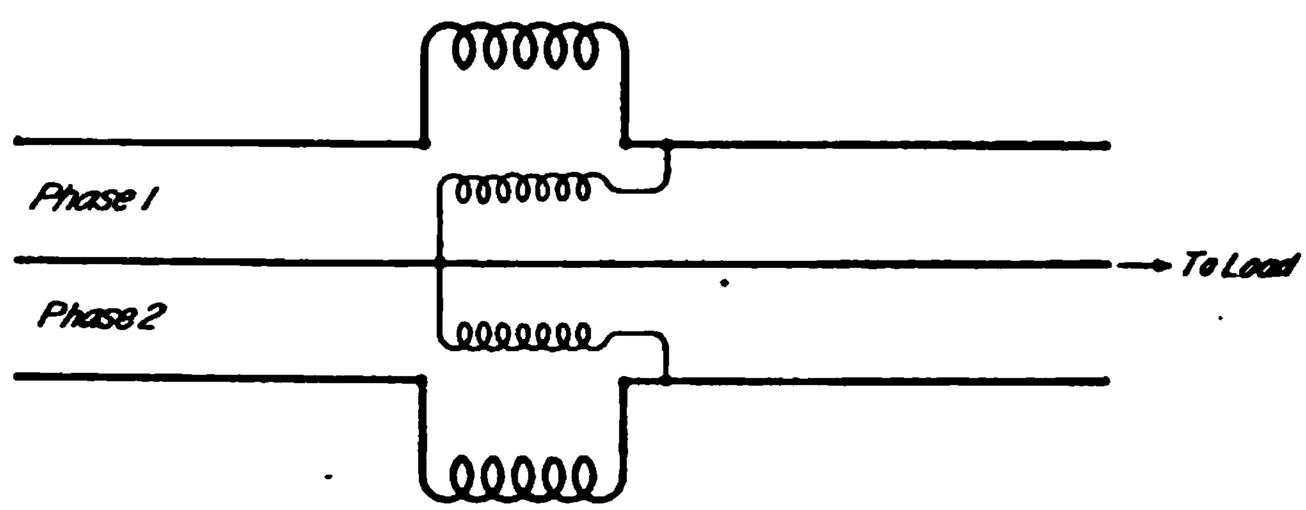


FIG. 44

the induction type are made, in which two sets of series-coils and two potential coils act on a common armature, thus practically combining two single-phase meters into a single meter, so that only one instrument is required to measure the energy no matter what the power factor may be or how unbalanced the current in the two phases.

54. Induction Wattmeter for Unbalanced Polyphase Circuits.—Fig. 45 shows a General Electric polyphase meter of the induction type for measuring energy supplied to unbalanced two-phase, three-phase, or monocyclic circuits. It operates on exactly the same principle as the single-phase induction wattmeter and is essentially two sets of single-phase meter coils acting on a common disk armature *a*. The two potential coils *b*, *b* are shown above the disk; they are connected in series with the reactance

coils *c*, *c*. There are four current coils, two of which are shown at *d*, *d*. A pair of current coils is situated under each potential coil and current is supplied to the front pair by means of the conducting strips *e*, *e*. The ends of the series-coils connect to terminals *f*, *f*, *g*, *g*, to which the mains are connected; *h* is one of the two magnets that retard the disk. Each set of coils *b*, *d*, *d* constitutes a single-phase induction meter, and as both these act on the same disk *a*, it follows that the resultant effort that turns

Fig. 45

the disk is a combination of the efforts exerted by the two sets of coils, and the record given by the meter is, therefore, a true indication of the watts supplied. In Fig. 45, one set of series-coils *d*, *d* would be connected in series with phase *1*, and the other set in series with phase *2*. The potential coils *b*, *b* would be connected across the two phases. In a three-phase circuit the two sets of series-coils would be connected in series with the two outside wires, and the potential coils would be connected between the outside wires and the middle wire.

55. Use of a Single Wattmeter on Two-Phase Circuit.—Figs. 46 and 47 show two methods of measuring the power on a two-phase circuit with a single wattmeter; these can be used in case the load is balanced. In Fig. 46, the current coil is connected in the common return wire, and a reading is first taken with the potential coil connected across phase *2*, as shown by the full line. The connection *a* is then transferred to *a′*, thus connecting the potential coil across the other phase. The

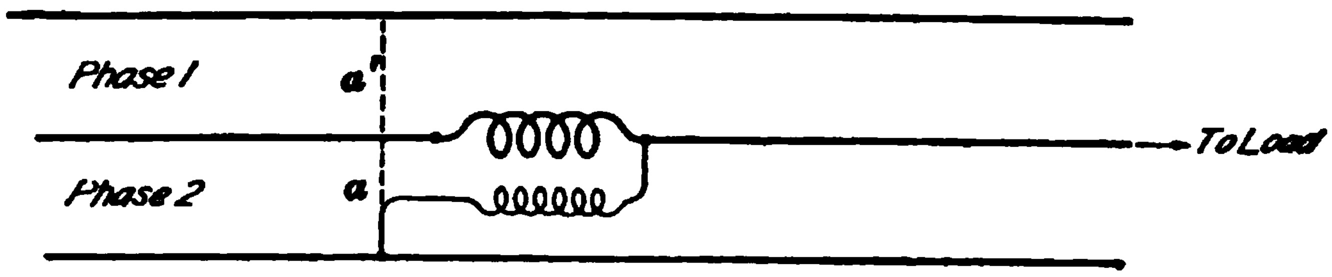


FIG. 46

sum of the two readings gives the total power supplied no matter what the power factor of the load may be. In Fig. 47, the potential coil is connected across the outside wires, while the current coil is connected in the middle wire. The reading of the wattmeter gives the total number of watts because, if the system is balanced, the resultant current will differ in phase from the resultant E. M. F. by the same amount that the current in each phase differs from

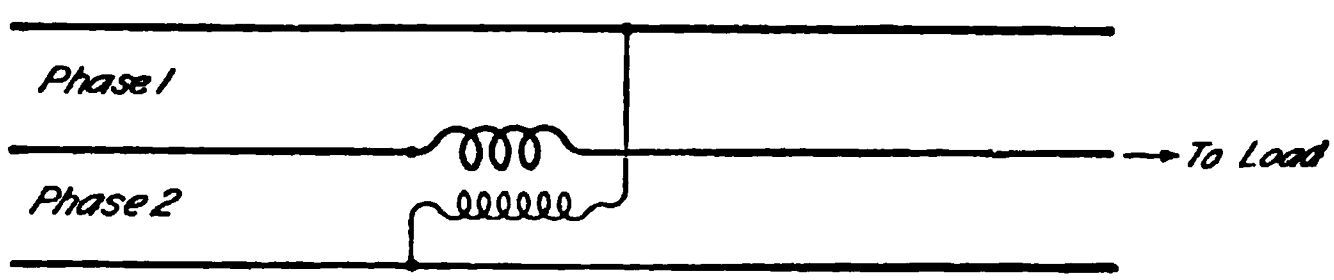


FIG. 47

the E. M. F. of each phase. The resultant E. M. F., i. e., the E. M. F. E' between the outside wires, is $\sqrt{2}\,E$, where E is the E. M. F. of each phase. The resultant current I', i. e., the current in the middle wire, is $\sqrt{2}\,I$, where I is the current in each phase. The reading of the wattmeter is $E'\,I'\cos\phi$, where ϕ is the angle of lag. The watts supplied to phase *1* are $E\,I\cos\phi$ and the same to phase *2*, so that the total watts supplied are $2\,E\,I\cos\phi$. Now $E' = \sqrt{2}\,E$ and $I' = \sqrt{2}\,I$; hence, $E'\,I'\cos\phi = \sqrt{2}\,E\,\sqrt{2}\,I\cos\phi = 2\,E\,I\cos\phi$.

That is, a single wattmeter connected as shown in Fig. 47 indicates the total number of watts supplied provided the load is balanced. These methods of using a single wattmeter are convenient, but it is always best to use the two wattmeters if they can be obtained, because one cannot always be certain that the load is balanced.

MEASUREMENT OF POWER ON THREE-PHASE CIRCUITS

56. Power may be measured on a three-phase circuit by using one, two, or three wattmeters. Two-wattmeter measurements are the most common, as the use of a single wattmeter requires either that the load be exactly balanced, or that the connections be transferred from one phase to another and the load kept constant during the change.

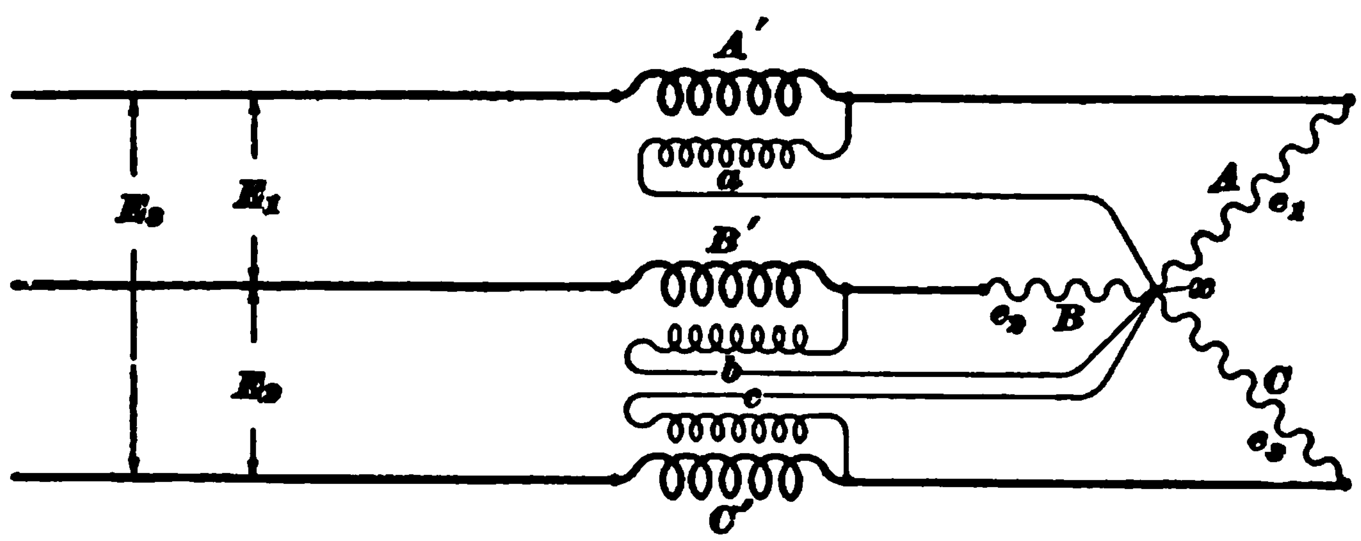


FIG. 48

57. Use of Three Wattmeters.—Let $A\ B\ C$, Fig. 48, represent the three windings of a Y-connected three-phase alternator. In a balanced system, e_1, e_2, and e_3 being equal, the line E. M. F.'s E_1, E_2, E_3 are also equal, and are equal to the E. M. F. in one winding multiplied by $\sqrt{3}$. The current in each line will be the same as the current in the winding to which it is connected, and in a balanced system the three currents will be equal. Three wattmeters with their current coils $A'\ B'\ C'$ connected in the lines and their potential coils $a\ b\ c$ connected across the corresponding winding, will measure the power delivered no matter whether the load be balanced or unbalanced, inductive or non-inductive.

It is evident from the way in which the wattmeters are connected that the potential applied to the pressure coil is equal to that generated in the winding with which the current coil is in series. Hence, the reading of wattmeter A' will be $e_1\, i_1 \cos \phi$, where ϕ is the angle of lag between the current and E. M. F. The other two meters will give the power developed in phases B, C, and the sum of the three readings gives the total power. If the load were exactly balanced it would be necessary to use but one wattmeter and multiply its reading by 3 to obtain the total power. In case $A\ B\ C$ represented the windings of an induction motor, synchronous motor, transformers, or in fact a load of any kind, this method of measuring the power could

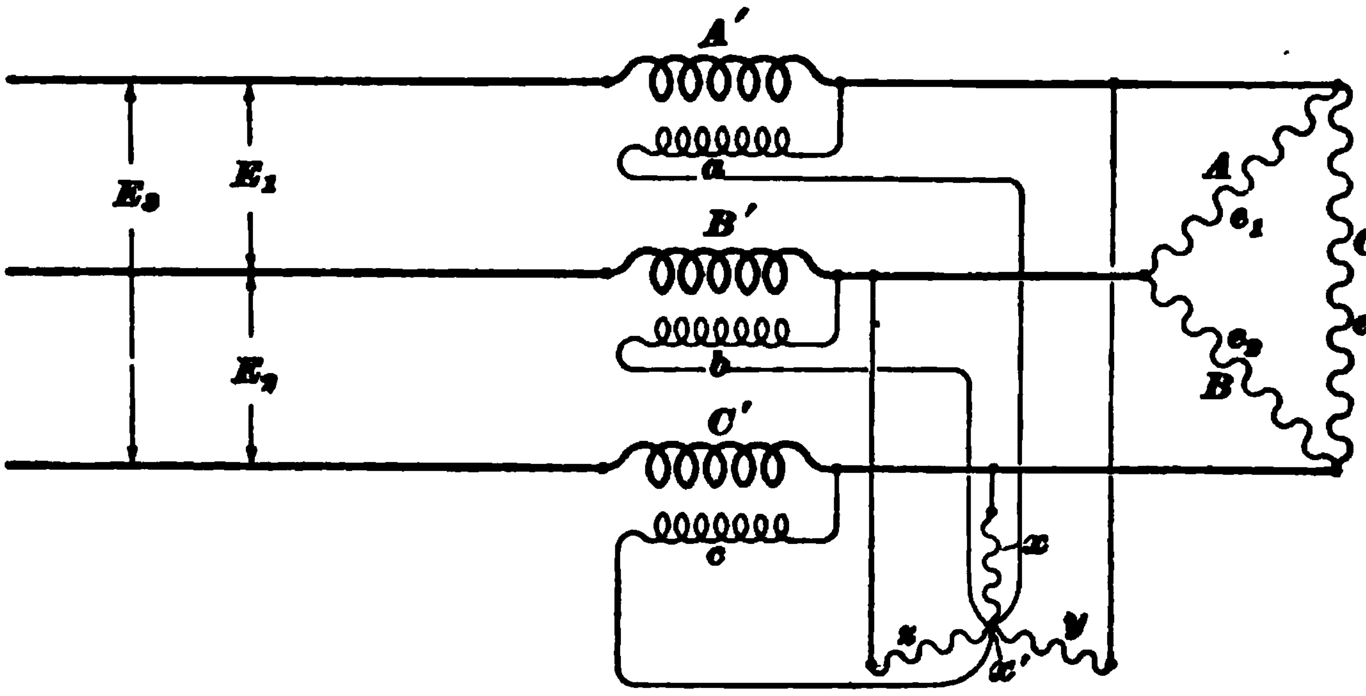


FIG. 49

be applied, though, as shown later, it is possible to measure an unbalanced three-phase load with two meters, and the three-meter method is therefore little used.

In most cases it is not possible to get at the neutral point x, Fig. 48, to connect the potential coils. In such cases an artificial neutral point may be obtained, as shown in Fig. 49, by connecting three non-inductive resistances x, y, z across the three phases, and attaching their neutral point x' to the potential coils. These resistances might be made up of wire wound non-inductively, or of incandescent lamps. The sum of the three wattmeter readings would then give the total power supplied as before.

58. Use of Single Wattmeter With Y Resistance. If the load were balanced, it would be sufficient in Fig. 49 to use but one wattmeter and multiply its reading by 3.

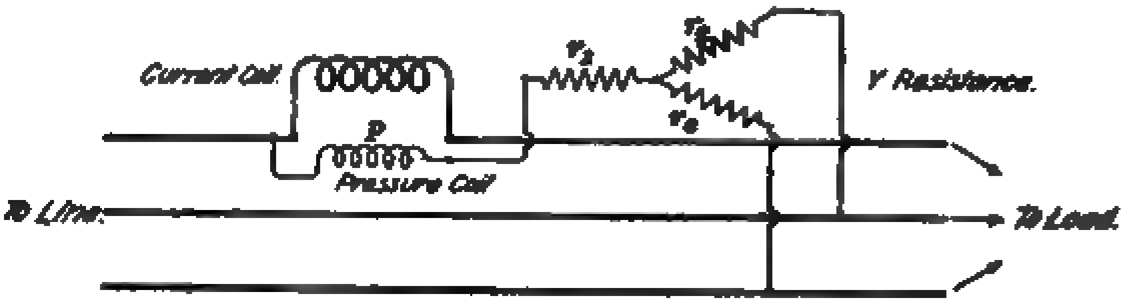


Fig. 50

Fig. 50 shows the connections for a single wattmeter used in this way. The resistances r_2, r_3 correspond to resistances x, z. Resistance r_1 is the usual protective resistance in series with the movable wattmeter coil. Fig. 51 shows a Thomson recording wattmeter with Y resistance; a is the starting coil of the wattmeter intended to compensate for the friction and to secure more accurate readings on light loads. By comparing Figs. 50 and 51 it will be seen that the connections are identical, the recording meter being connected in exactly the same way as the indicating instrument. Fig. 52 shows the connections of a recording meter on a three-phase balanced circuit where the pressure is over 500 volts; the potential circuit is here supplied through the small step-down transformers t, t. For very

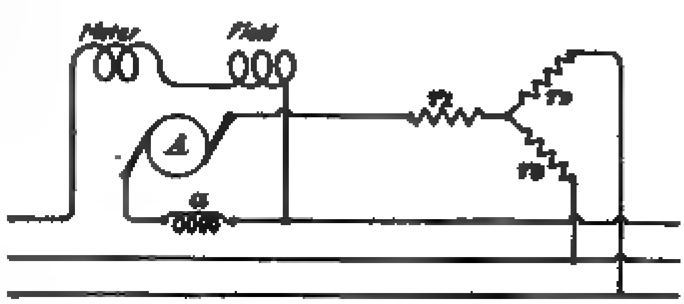


Fig. 51

high-pressure circuits, the current coils would be connected to the secondaries of current transformers instead of directly in the circuit. Fig. 53 shows the connections of a Wagner indicating wattmeter for measuring the power on a balanced three-phase circuit. The stationary current coils A, A are connected in series with the secondary of a current transformer C instead of being placed directly in the circuit. The movable potential coil B is supplied with current from the small transformers D, D. A Y resistance is used, the two branches being in the separate cage E; the protective resistance F is used to limit the current in the potential coil.

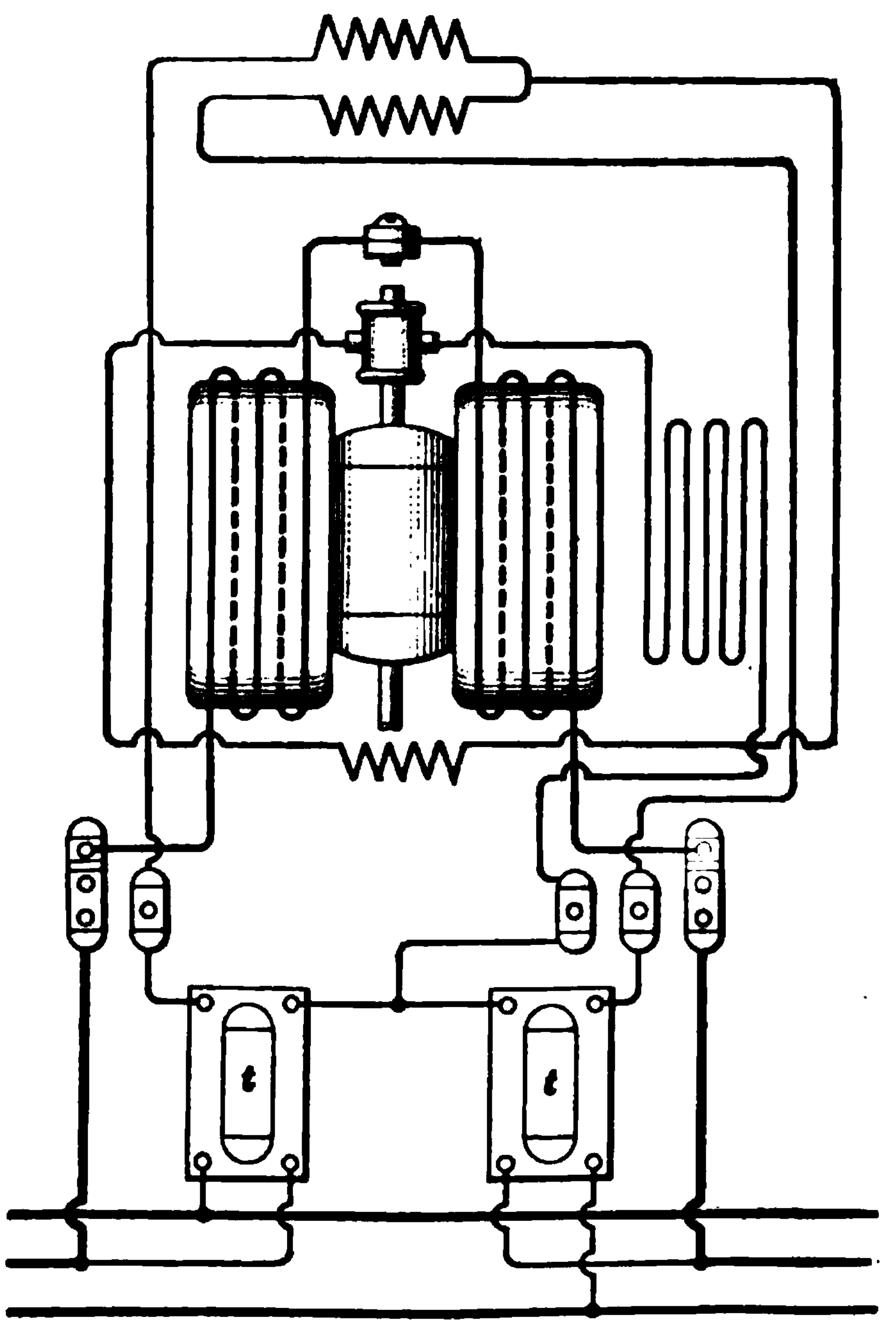


FIG. 52

59. Use of Two Wattmeters on Three-Phase Circuits.—The most common method of measuring the power supplied to a three-phase circuit is by means of two wattmeters connected as shown in Fig. 54. The current coils A, B are connected in two of the lines, and the potential coils between these two lines and the third line. If the power factor of the load is over .5, i. e., if the angle of lag is less than 60°, the sum of the two wattmeter readings gives the power supplied. If the power factor is less than .5, i. e., if the angle of lag is greater than 60°, the difference of the readings gives the power.

Since the coil *A*, Fig. 54, is connected in one line and the potential coil *a* between the outside and middle lines, it is evident that even on a non-inductive load the current in *A* is not in phase with the current in *a*. On a non-inductive load

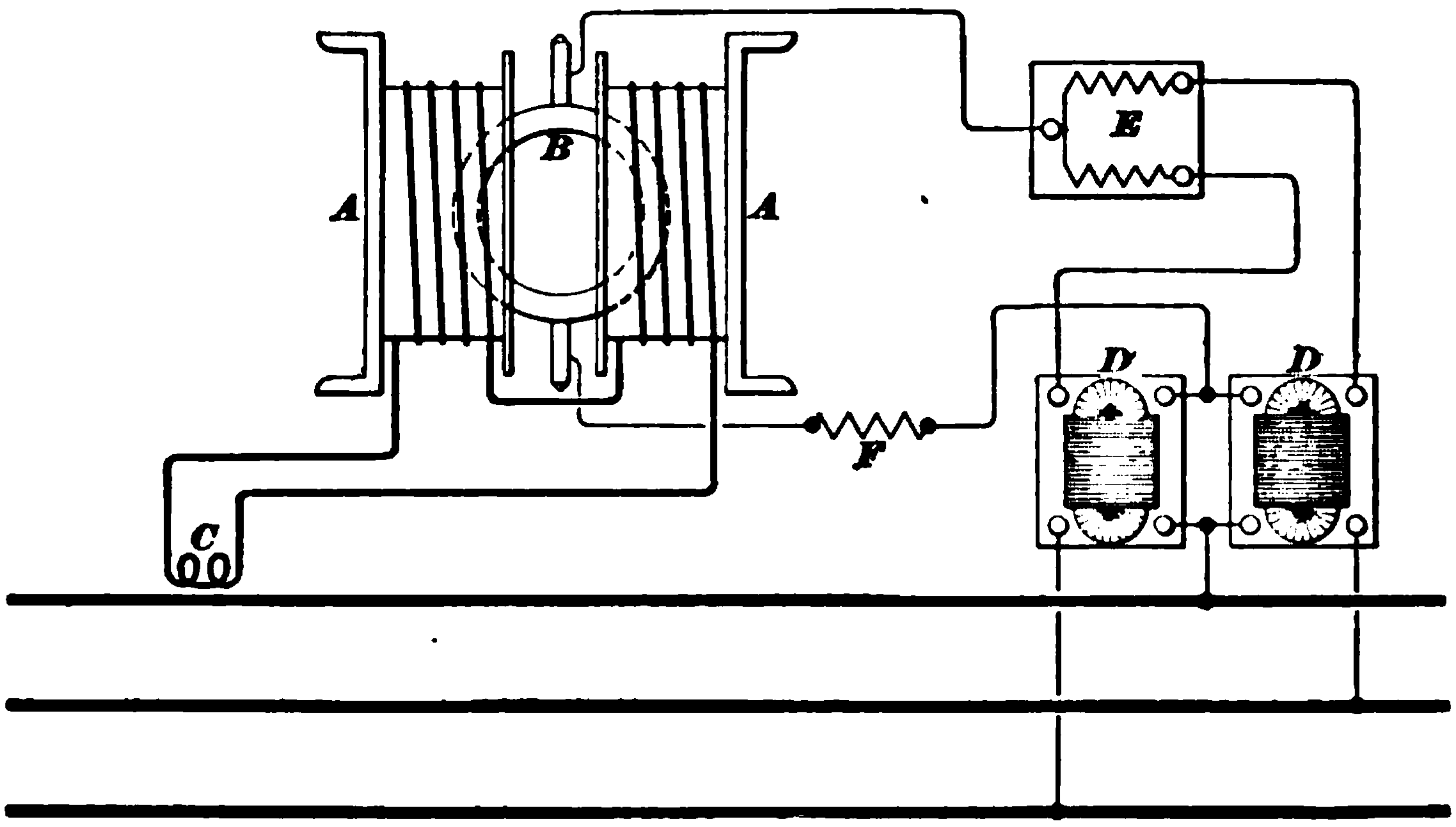


FIG. 53

the current in *A* will differ in phase from the E. M. F. between *1* and *2* by 30°, and the current in *B* will differ in phase from the E. M. F. between *2* and *3* by 30°. In Fig. 55, suppose that *x* represents the neutral point of the system, and that the lines *x–1′*, *x–2′*, *x–3′* represent the three voltages, differing

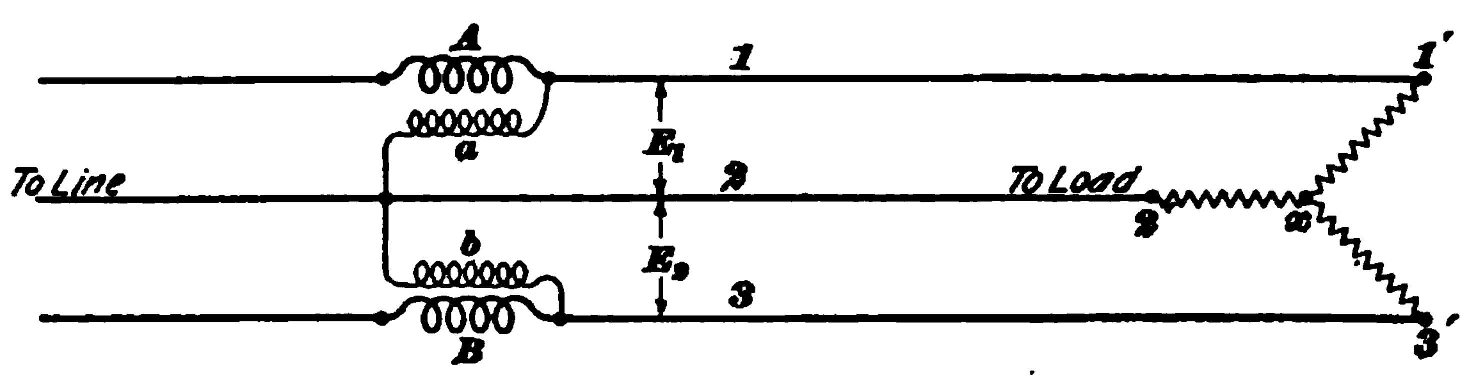


FIG. 54

in phase by 120°. Then the voltage between lines *1* and *2* is equal to *1′–x* plus *2′–x*, and is found by producing *x–2′* backwards and finding the resultant *x–4*. This resultant is 30° behind the voltage *x–1′*. The voltage between lines

2 and 3 is x–$5'$ found by producing x–$3'$ backwards and combining with x–$2'$. Since the wattmeters are connected symmetrically, as in Fig. 54, we must consider the E. M. F. acting on coil b as the E. M. F. taken in the direction 3–2 or $3'$–$2'$ instead of $2'$–$3'$, since we have taken the other E. M. F. in the direction 1–2 or $1'$–$2'$. The E. M. F. acting on coil b will therefore be represented by x–$6'$ equal and opposite to x–$5'$. Now, when the load is non-inductive, the current in coils A and B is in phase with the E. M. F.'s x–$1'$ and x–$3'$, so that the E. M. F. acting on coil a is 30° behind the current in a, and the E. M. F. acting on b is 30° ahead of the current in B.

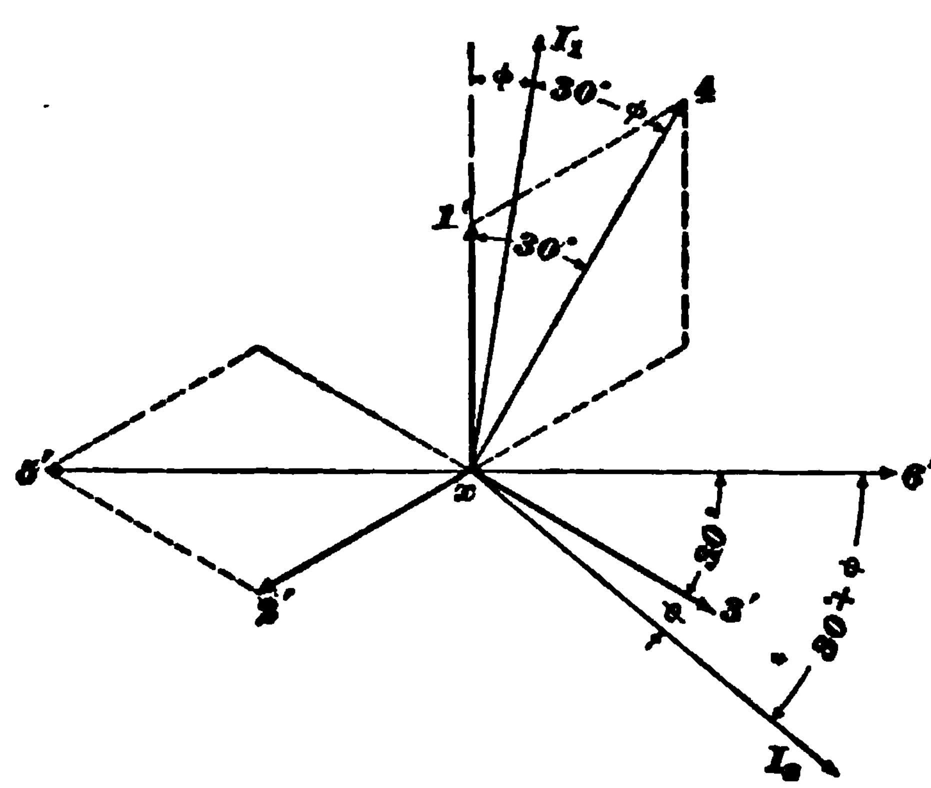


FIG. 55

If the load is inductive, the currents in the coils A, B instead of coinciding in phase with x–$1'$ and x–$3'$ will lag by an angle ϕ, cos ϕ being equal to the power factor of the load. The current will then be represented by the lines x–I_1 and x–I_3 lagging ϕ degrees behind x–$1'$ and x–$3'$. Lines x–4 and x–$6'$ represent the E. M. F.'s applied to coils a, b so that with an inductive load the phase difference between the currents in A and a is $30° - \phi$, and between the currents in B and b it is $30° + \phi$. If we represent the pressures x–$1'$, x–$2'$, x–$3'$, etc. by ε, the pressure x–4 or the line pressure will be $\sqrt{3}\ \varepsilon$. The watts indicated by A will be $\sqrt{3}\ \varepsilon I_1$ cos

$(30° - \phi)$, and the watts indicated by B, $\sqrt{3}\, \varepsilon\, I_s \cos(30° + \phi)$, and the sum of these two readings gives the power.*

60. It is now easily seen why a power factor of less than .5 will give a negative reading on one of the wattmeters. If the lag is 60°, the current in B differs in phase from that in b by $30 + \phi = 90°$; no effort is exerted on the swinging coil of the wattmeter and no deflection is given. If the lag becomes greater than 60° a torque is exerted in the reverse direction on the movable coil, and a negative deflection is obtained. For power factors greater than .5, both wattmeters will give positive readings, but their readings will not be alike and both positive unless ϕ becomes zero, i. e., unless the power factor is 100 per cent. or unity. If the angle of lag becomes 90°, both wattmeters will read alike, but one will be positive and the other negative, so that their sum will be zero. This is as it should be, because when the lag is 90° the current flowing in the circuit is wattless and no power is expended. The conditions under which the test is made will nearly always indicate whether or not a negative reading is to be expected. If there is any doubt on the matter, connect the meters to a load of lamps and after all connections have been made so that both meters read properly, take off the lamps and connect the load under test. If one of the meters gives a reverse reading it shows that the reading is negative and that the difference in the two readings must be taken to give the number of watts supplied. Fig. 56 shows the connections of a Wagner indicating

*That the sum of these two readings gives the power is easily shown for the case of a balanced circuit where $I_1 = I_2$. We have, power $= W = \sqrt{3}\, \varepsilon\, I_1 \cos(30° - \phi) + \sqrt{3}\, \varepsilon\, I_1 \cos(30° + \phi)$. From trigonometry we know that $\cos(30° + \phi) = \cos 30° \cos \phi - \sin 30° \sin \phi$, and $\cos(30° - \phi) = \cos 30° \cos \phi + \sin 30° \sin \phi$. Substituting these values for $\cos(30° + \phi)$ and $\cos(30° - \phi)$, we have

$$W = 2\sqrt{3}\, \varepsilon\, I_1 \cos 30° \cos \phi,$$

but $\cos 30° = \frac{\sqrt{3}}{2}$; hence, $W = 3\, \varepsilon\, I_1 \cos \phi$, but $\varepsilon\, I_1 \cos \phi$ is the power in one phase, and $3\, \varepsilon\, I_1 \cos \phi$ is the total power, so that the sum of the two wattmeter readings gives the total power supplied to the circuit.

wattmeter for measuring the watts on a three-phase circuit with balanced or unbalanced loads and with any power factor. It consists essentially of two wattmeters; $A\,A$, $A'\,A'$ are the two sets of current coils and B, B' the two movable potential coils mounted on the same shaft. The torque due to the two wattmeters is thus added or subtracted, as the case may be, and the pointer attached to the shaft indicates the actual number of watts expended. The current coils are supplied from current transformers, and each of the movable coils has a non-inductive resistance in series with it. This

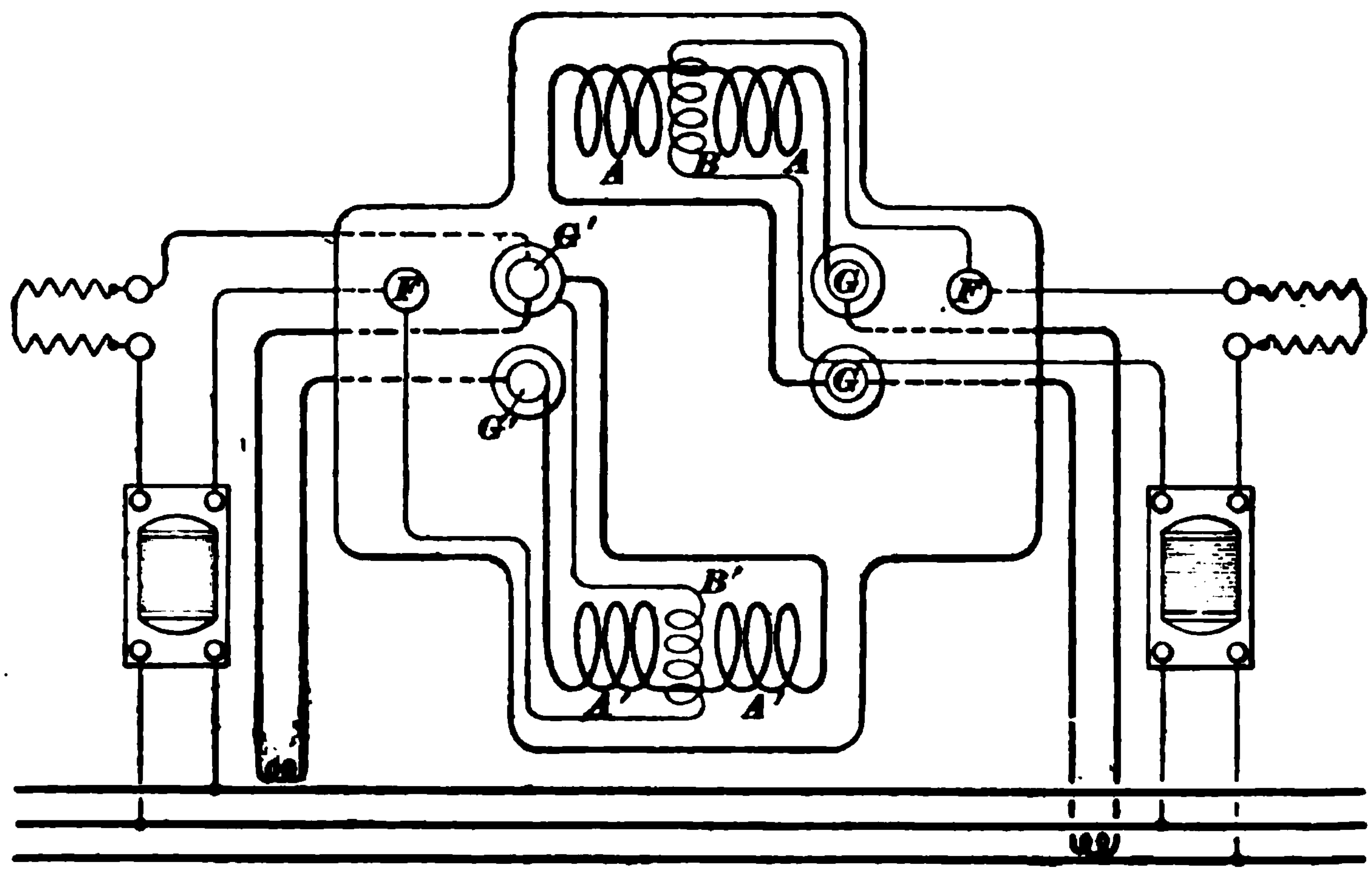


FIG. 56

wattmeter is also suitable for measurements on an unbalanced two-phase system.

The recording wattmeter, shown in Fig. 45, is used largely for measurements on three-phase circuits. Since the two wattmeter elements act on a common armature, if one of them gives a negative turning effort, the net turning effect on the disk is reduced and the record on the dial is due to the difference of the effects of the two wattmeters. The instrument, therefore, gives an accurate record, no matter what the power factor may be.

61. Measurement of Power Factor.—The fact that the ratio of the two wattmeter readings, Fig. 54, varies with the power factor of the load affords a method of determining the power factor from the wattmeter readings.* Of course if ammeter and voltmeter readings are available the power factor can be calculated, since it is equal to $\frac{\text{true watts}}{\text{apparent watts}}$ the true number of watts being obtained from the wattmeter readings and the apparent watts from the voltmeter and ammeter readings. For a three-phase circuit the apparent watts would be $\sqrt{3}\,E\,I$. When two wattmeters are used, as shown in Fig. 54, the power factor of a three-phase circuit can be determined from the ratio of the readings alone, and ammeter and voltmeter readings are not necessary. The ratio of the readings is

$$\frac{\sqrt{3}\ \varepsilon\, I \cos(30° + \phi)}{\sqrt{3}\ \varepsilon\, I \cos(30° - \phi)} = \frac{\cos(30° + \phi)}{\cos(30° - \phi)};$$

$$\frac{\cos(30° + \phi)}{\cos(30° - \phi)} = \frac{\cos 30° \cos\phi - \sin 30° \sin\phi}{\cos 30° \cos\phi + \sin 30° \sin\phi}$$

but $\cos 30° = \frac{\sqrt{3}}{2}$, and $\sin 30° = \frac{1}{2}$; hence,

$$\frac{\cos(30° + \phi)}{\cos(30° - \phi)} = \frac{\frac{\sqrt{3}}{2}\cos\phi - \frac{1}{2}\sin\phi}{\frac{\sqrt{3}}{2}\cos\phi + \frac{1}{2}\sin\phi} = \frac{\sqrt{3}\cos\phi - \sin\phi}{\sqrt{3}\cos\phi + \sin\phi}$$

Now if we take the expression $\frac{\sqrt{3}\cos\phi - \sin\phi}{\sqrt{3}\cos\phi + \sin\phi}$, and substitute different values for ϕ, we will get the ratio of the wattmeter readings corresponding to those values. For example, if $\phi = 60°$ we have ratio of wattmeter readings

$$= \frac{\sqrt{3} \times \frac{1}{2} - \frac{\sqrt{3}}{2}}{\sqrt{3} \times \frac{1}{2} + \frac{\sqrt{3}}{2}} = \frac{0}{\sqrt{3}} = 0.$$

An angle of lag of 60° corresponds to a power factor of .5. For an angle of lag of

*E. J. Berg, Electrical World and Engineer, Vol. XXXIX.

30°, power factor = cos 30° = .866, we have ratio of readings

$$= \frac{\sqrt{3} \times \frac{\sqrt{3}}{2} - \frac{1}{2}}{\sqrt{3} \times \frac{\sqrt{3}}{2} + \frac{1}{2}} = \frac{1}{2}$$

By thus taking different values of the power factor we can plot a curve, Fig. 57, showing the relation between the ratio of the wattmeter readings and the power factor of the load.

EXAMPLE.—The power supplied to a three-phase induction motor is measured by means of two wattmeters connected as shown in Fig. 54.

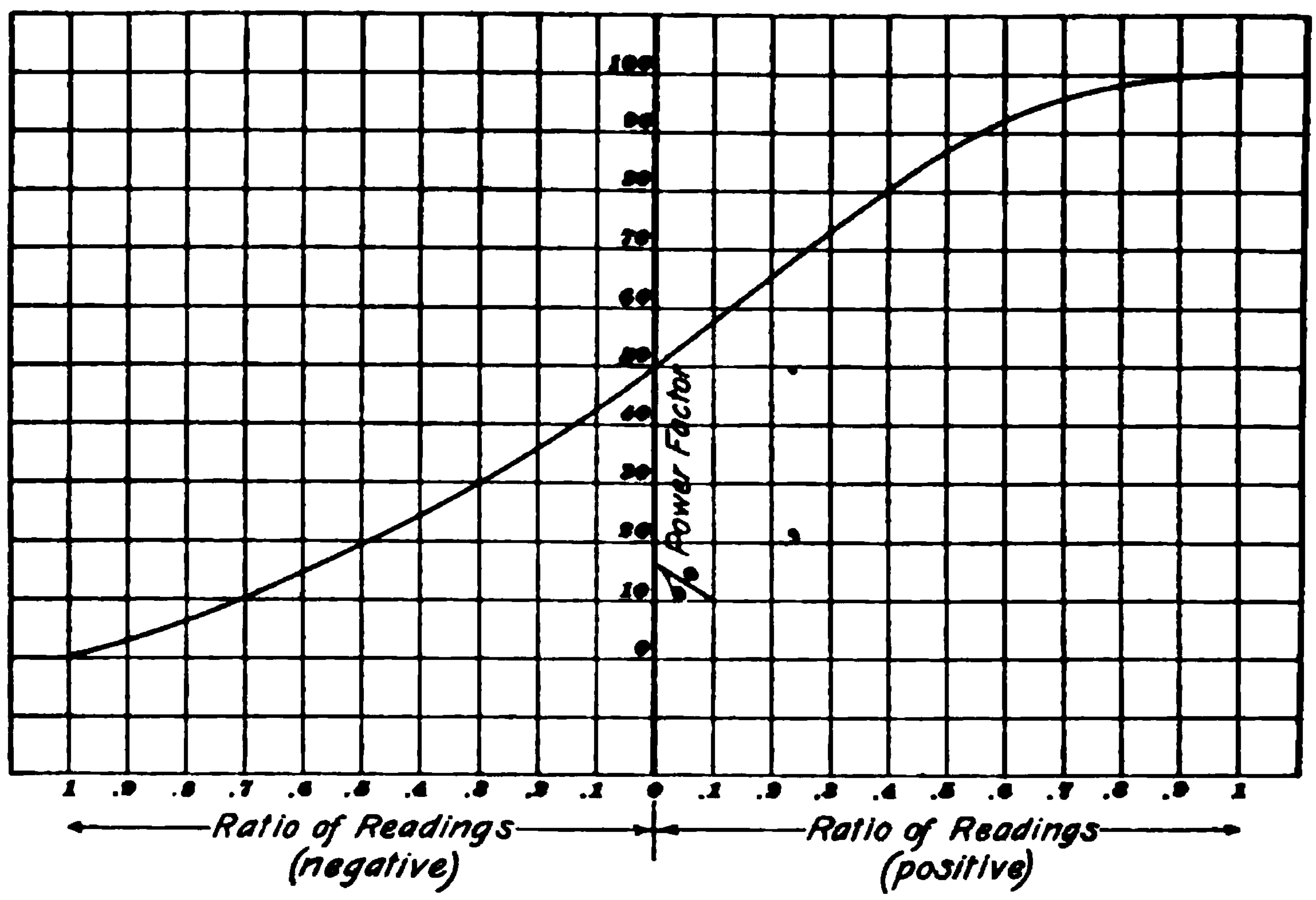


FIG. 57

The reading of A is 2,000 watts, and that of B 6,000 watts. What is the power factor of the motor corresponding to this load, and what is the total power supplied to the motor?

SOLUTION.—The ratio of the two readings is $\frac{2,000}{6,000}$ = .333 and is positive, because both readings are positive. Hence, referring to Fig. 57, we take the ratio .333 on the right of the center line, and find that the power factor corresponding to this ratio is about .74. The total power supplied to the motor will be 2,000 + 6,000 = 8,000 watts.

62. Power-Factor Indicators.—The power-factor indicator made by the General Electric Company and used on

three-phase circuits is based on the foregoing principle. It consists of a fixed current coil, connected in series with the middle line, within which two potential coils are mounted on a vertical shaft. These coils are connected between the middle and outside lines. The resultant effort tending to deflect the shaft will evidently vary with the power factor, because the phase relation of the currents in the movable coils to the current in the fixed coil will change with the power factor and the instrument can be calibrated so that the pointer attached to the movable coils will indicate the power factor.

Another type of power-factor indicator that is commonly used is the same in construction as an indicating wattmeter,

Fig. 58

except that the potential coil is connected in series with an inductance so that the current in it is 90° behind the current in the main coils when the power factor is 1. The result is that with a power factor of 1 there is no deflection of the pointer because there is no torque action between the two coils. With a power factor less than 1, lagging current, the pointer swings in one direction and with a power factor greater than 1, leading current, the pointer swings in the other direction. Fig. 58 shows the front of a Wagner power-factor indicator operating on this principle.

63. Measurement of Power With One Wattmeter. The power supplied to a balanced three-phase load may be measured with a single wattmeter, as shown in Fig. 59, by

first taking a reading with the potential coil connected at c and then quickly transferring the connection to c'. The sum of the two readings will give the power if the power factor is over .5; if less than .5, the difference in the readings would

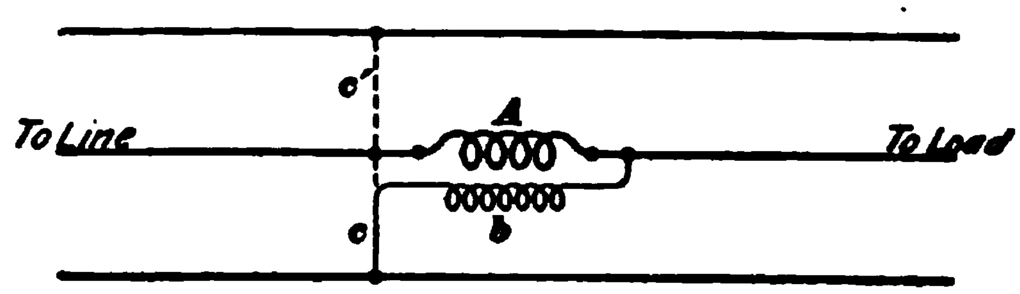


FIG. 59

be taken. It is necessary, however, to use two wattmeters unless the load can be kept constant while the connections are being changed or in case the load is not balanced.

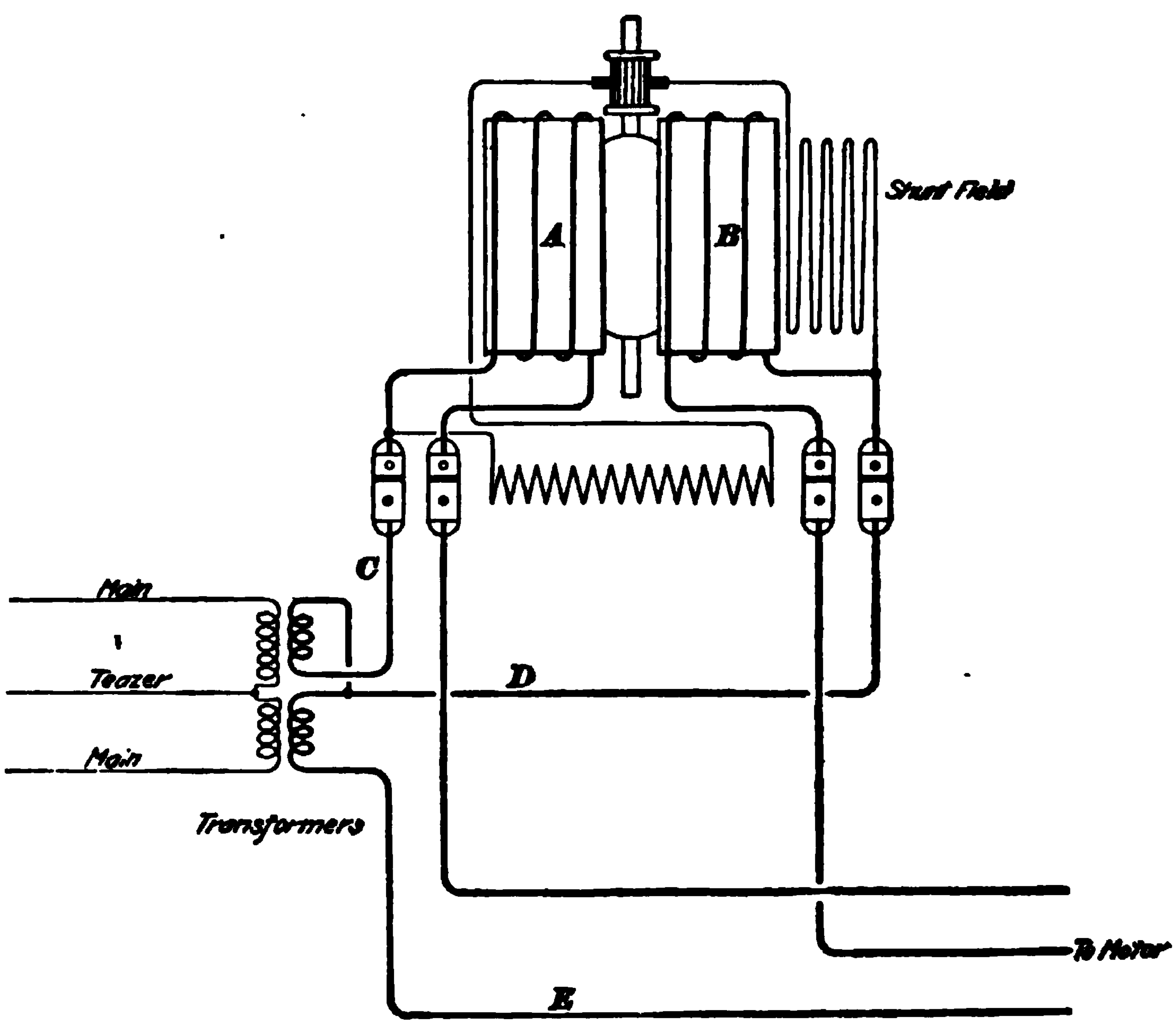


FIG. 60

64. Power Measurement on Monocyclic Circuit. Fig. 60 shows the connections for a Thomson recording wattmeter measuring energy supplied to a motor operated on the monocyclic system. The meter has two coils A, B,

which are connected in series with two of the lead wires running to the motor. As shown in the figure, the coils are in series with the leads *C*, *D*. If it is found that the speed of the meter diminishes when the load on the motor increases, field coil *A* should be connected in series with the main *E* instead of *C*.

INSTALLATION OF RECORDING WATTMETERS

65. Location.—Recording wattmeters should be located so that they can be easily reached either for the purpose of taking readings or inspecting them. They are too often placed in out-of-the-way places where they are very difficult to get at. They should not be placed in a position where they will be subjected to vibration as, for example, near a door that is continually being opened and shut. The location should be such that the meter will not be exposed to dampness or chemical fumes of any kind.

CONNECTIONS FOR METERS

66. The method of connecting meters to the circuit varies with the size and make of the meter. It is impossible to

Fig. 61

give here all the different connections and, moreover, it is not necessary or desirable to do so, as the makers send

Fig. 62

Fig. 63

out instructions with the meters, and these instructions are liable to change with changes in the construction of the meters. Therefore, only a few of the most common connections used on direct-current or single-phase alternating-current circuits will be described.

67. Connections for Thomson Recording Wattmeter.—Fig. 61 shows the method of connecting a Thomson recording wattmeter of small capacity on a two-wire circuit.

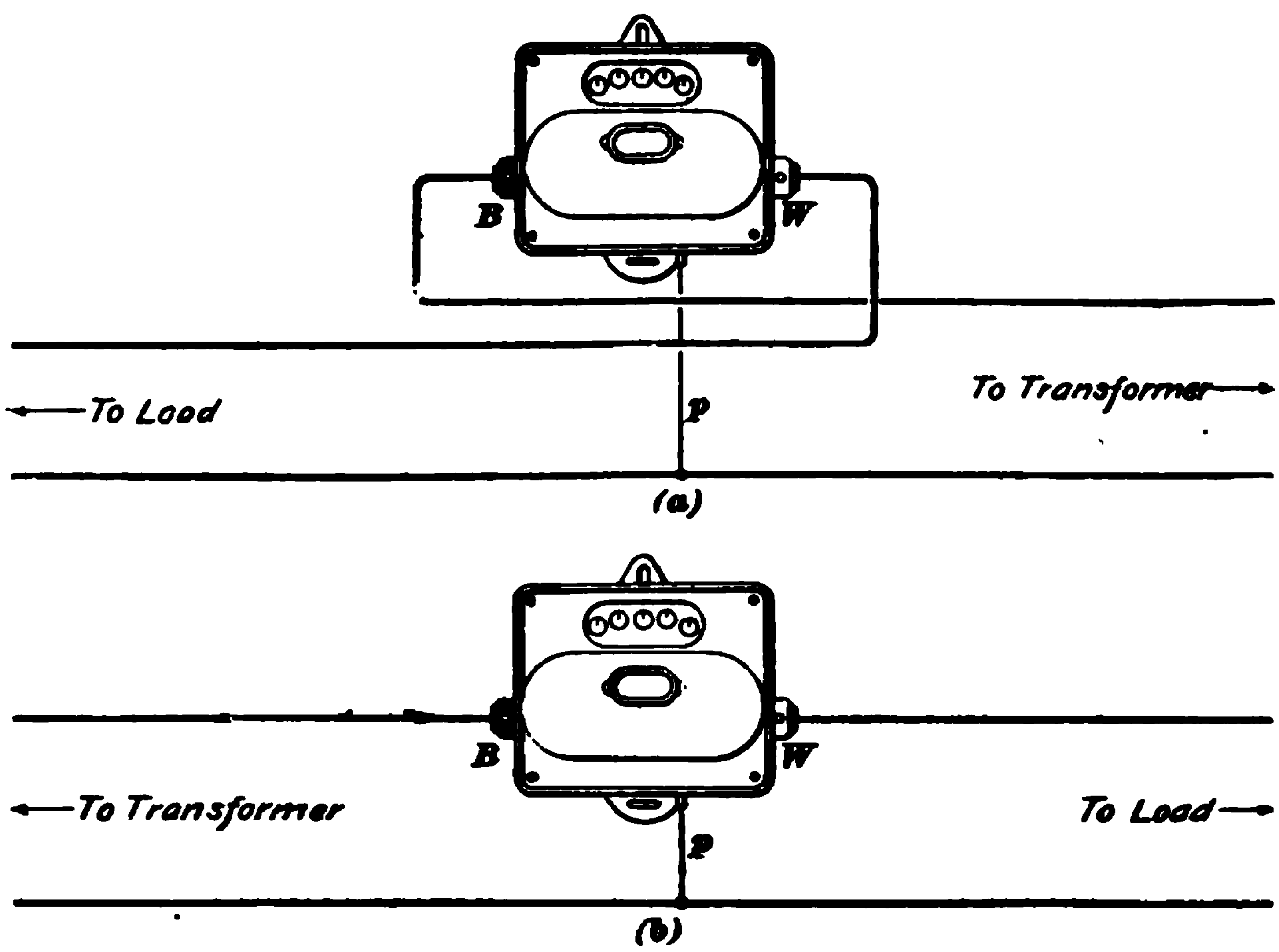


FIG. 64

When the meter is of large capacity, only one side of the circuit is run through it and a small potential wire is run in from the other side, so as to put the armature across the circuit. This method of connection is shown in Fig. 62. Fig. 63 shows a meter connected to a three-wire circuit.

68. Connections for Stanley Induction Wattmeter. Fig. 64 (*a*) and (*b*) shows the methods of connecting a Stanley wattmeter. The black terminal *B* on the meter must always connect to the transformer or other source of

E. M. F. The white terminal W connects to the load. It is necessary to have these connections correct or the meter will not rotate in the proper direction. The potential wire p connects from the meter to the wire that does not enter the meter.

The connections for induction wattmeters are much the same no matter what the make may be, the current coil or coils being connected in series with the circuit, and the potential coil across the circuit. What differences there may be are due to the manner in which the leads are brought

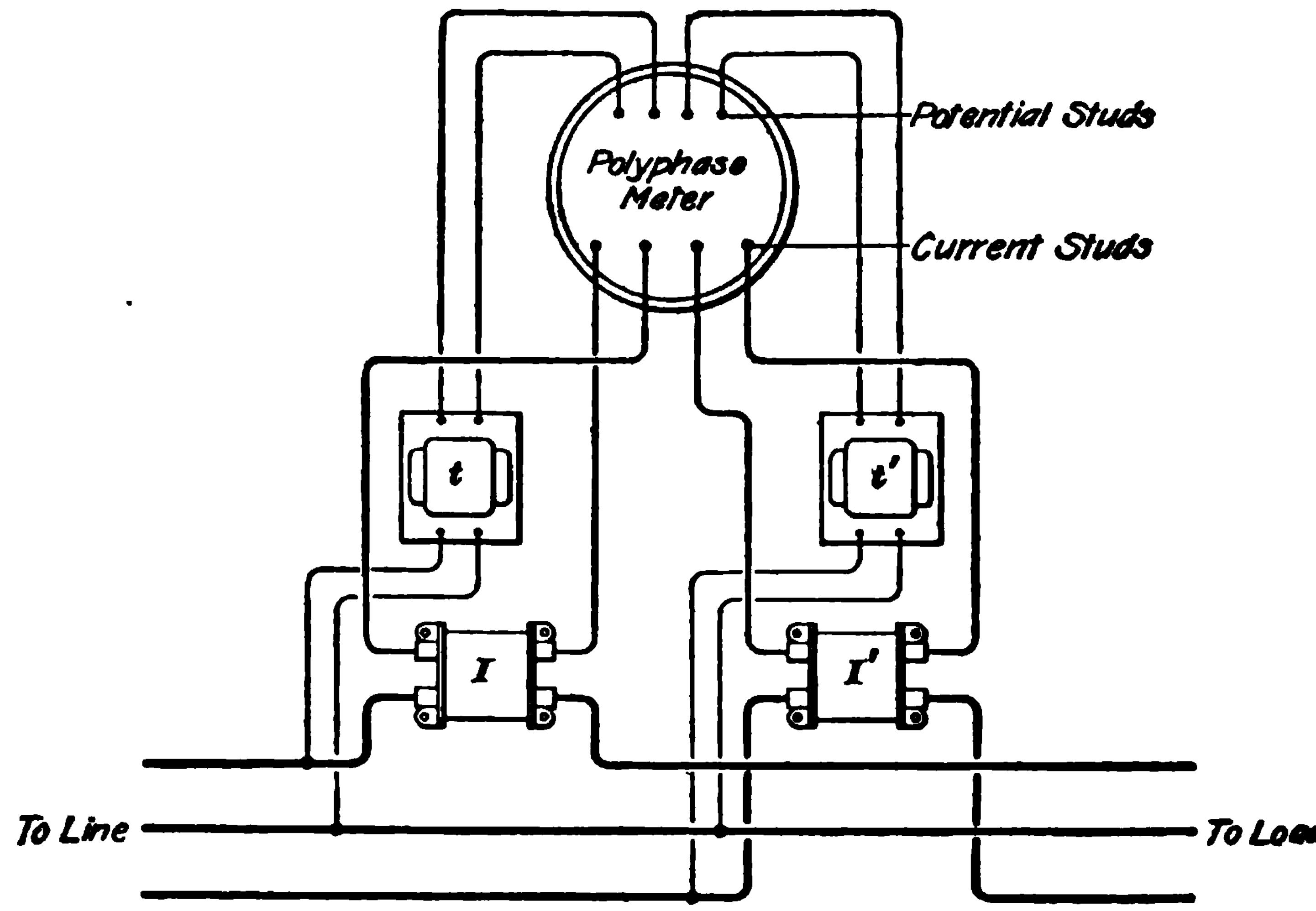


Fig. 65

out of the meter case. In most cases current transformers are used in connection with meters on high-tension lines, the current coils being connected in series with the secondary of a current transformer instead of in series with the main circuit. On high-potential circuits, the potential coils are supplied from potential transformers that step-down the voltage applied to the coils. Of course, when current and potential transformers are used in connection with a meter, the instrument is always calibrated so that it will take account of the current or voltage transformations and

indicate the number of watts in the main circuit. Fig. 65 shows the connections for a General Electric induction wattmeter of the polyphase type used on switchboards. In this case, potential transformers t, t' are used to step-down the voltage and current transformers I, I' to transform the current. The connections shown are such as would be used on a three-phase circuit or a three-wire, two-phase circuit with the common return wire in the middle.

TESTING AND ADJUSTING RECORDING WATTMETERS

69. Recording wattmeters should be checked up occasionally to see if they record correctly. If a rough test only is required the meter may be loaded with a specified number of lamps of which the power consumption per lamp is known; if a more accurate test is desired, the recording

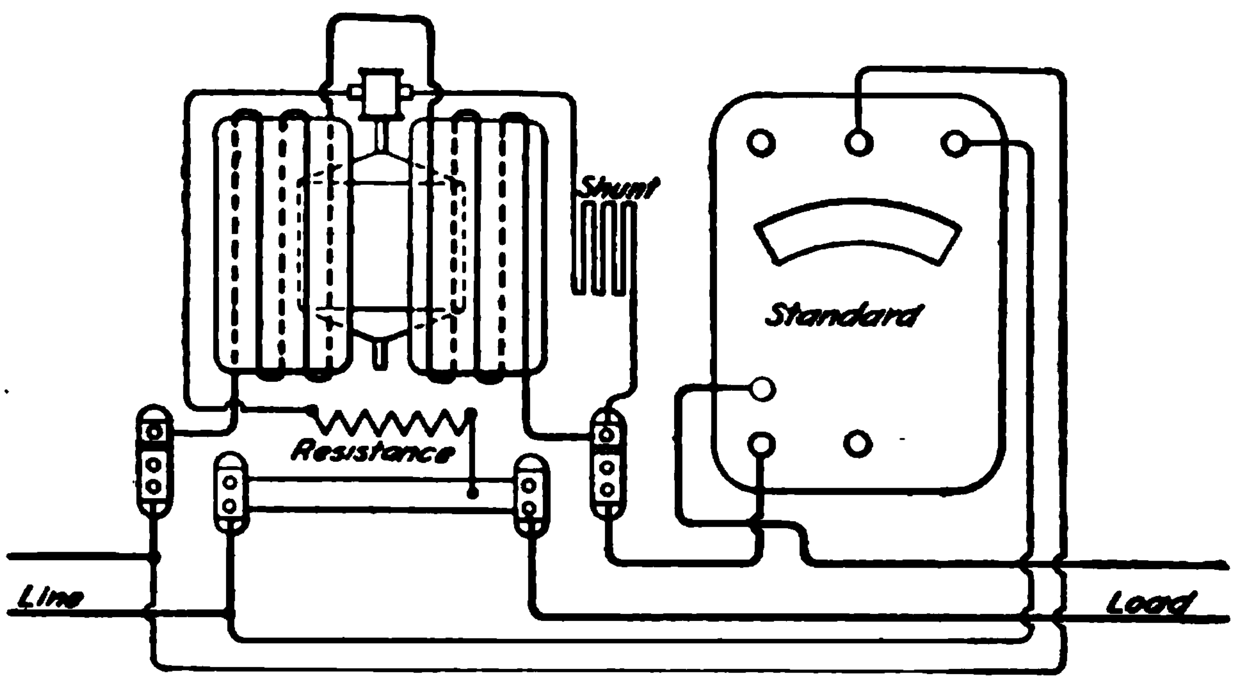


FIG. 66

meter is usually checked by comparing it with a standard indicating wattmeter.

70. Checking a Thomson Recording Wattmeter. Figs. 66 and 67 show connections for checking a two-wire Thomson meter. Either set of connections may be used. The meter is set to work on a load of lamps, or other convenient resistance, the standard direct-reading wattmeter

being connected as shown. A chalk mark is made on the meter disk, so that the revolutions may be easily counted, and the revolutions are taken for 40 to 60 seconds, the observer using a stop-watch. Another observer reads the standard instrument, and the load is kept as nearly constant as possible throughout the test. The meter watts may then be calculated from the following formula:

$$\text{Meter watts} = \frac{3{,}600\,R\,K}{T} \qquad (1)$$

where R = number of revolutions in T seconds;
T = time in seconds of R revolutions;
K = constant of meter.

The constant K used in formula **1** was, in the older types of meter, marked on the dial and was a number by which the dial reading had to be multiplied to give the true reading

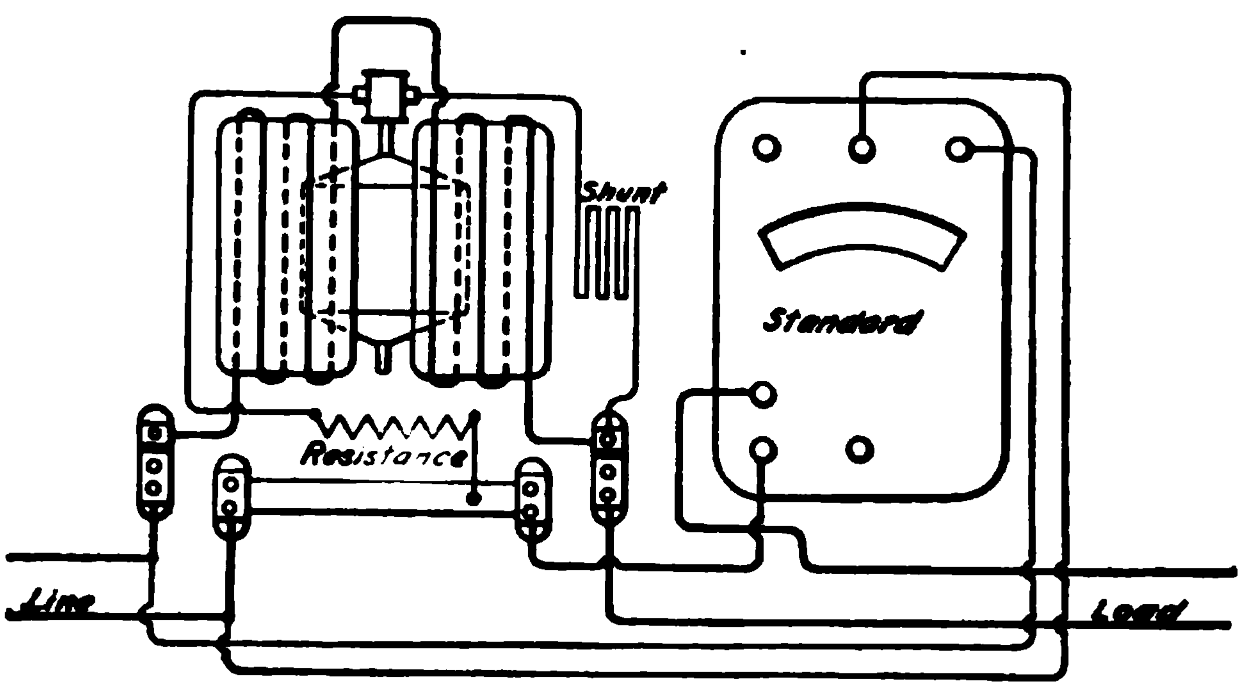


FIG. 67

of the meter. In recent types of Thomson meter, the gears in the recording train are arranged so that the dial reads directly and no constant is marked on it except in meters of large capacity. In recent meters the constant K used in formula **1** will be found marked on the revolving disk.

The actual watts are obtained from the standard meter; hence, the percentage by which the meter is correct is found by dividing the number of watts given by formula **1** by the number of watts given by the standard meter.

EXAMPLE.—The disk of a 10-ampere, 100-volt Thomson meter makes 10 revolutions in 60 seconds. The average number of standard watts as indicated by the standard meter is 303. Find the percentage error of the recording meter. The constant of the meter is $\frac{1}{2}$.

SOLUTION.—From formula **1**, we have

$$\text{Meter watts} = \frac{3{,}600 \times 10 \times \frac{1}{2}}{60} = 300$$

$$\tfrac{300}{303} = .99, \text{ or } 99\%. \quad \text{Ans.}$$

The meter is, therefore, 1 per cent. too slow, and the damping magnets should be shifted in a little so that the retarding action on the disks will not be so great.

71. If a standard wattmeter is not available for testing purposes, separate ammeters and voltmeters may be used for direct-current work, but they are not as convenient.

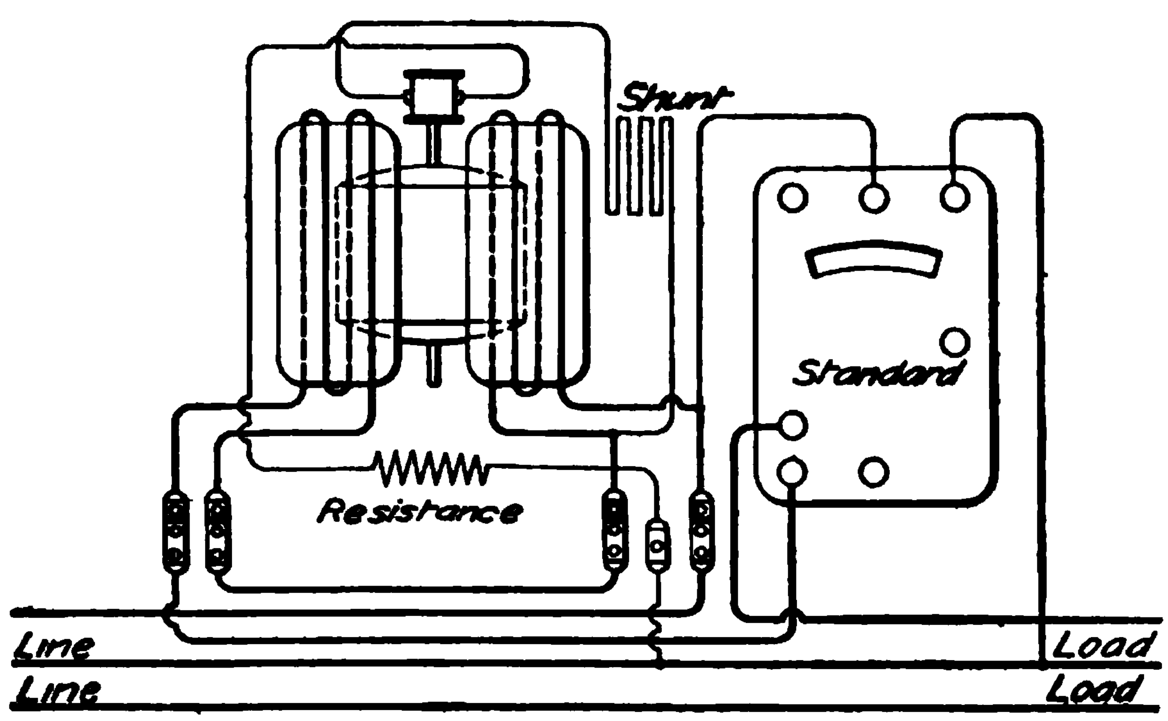


FIG. 68

In Figs. 66 and 67 it will be noticed that the energy consumed by the potential circuit of either meter is not measured by the other; that is, the current in the armature of the Thomson meter does not pass through the fields of the standard meter, neither does the current in the shunt of the standard pass through the field coils of the Thomson meter.

To test a Thomson meter used on a three-wire circuit (110–220 volts), the connections may be made as shown in Fig. 68. The potential circuits are wound for 110 volts. The field coils can, therefore, be connected in series, and the standard meter connected as shown. In formula **1**, however,

K should be taken as one-half the constant marked on the dial or disk. Aside from this, the meter can be tested in the same manner as a two-wire meter.

72. Checking a Stanley Wattmeter.—Fig. 69 shows the connections for checking a Stanley wattmeter and the connections for testing any two-wire induction wattmeter

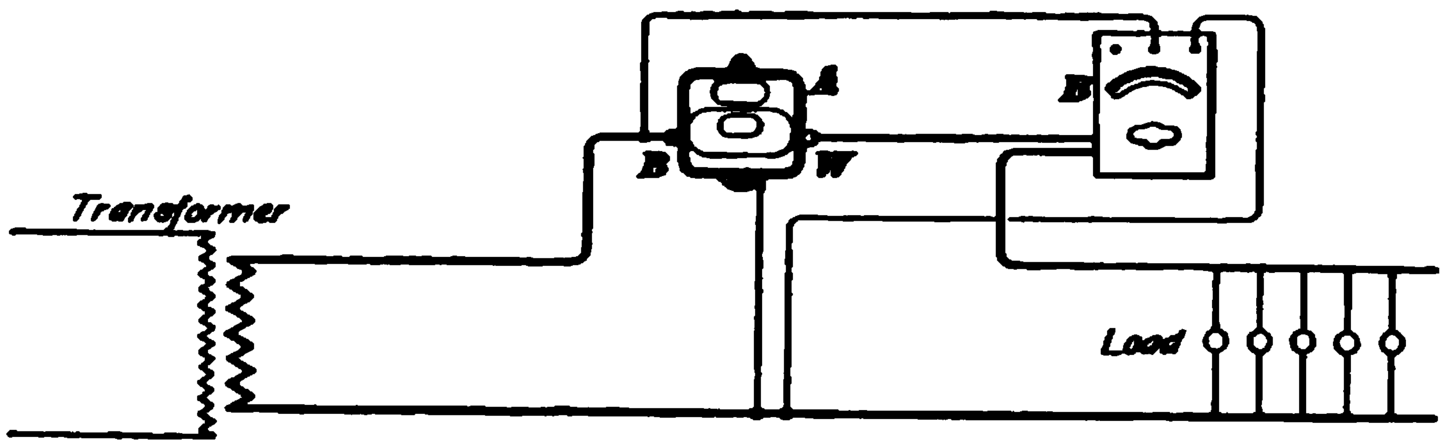


FIG. 69

would be very similar. A is the recording wattmeter and B the standard instrument. With the Stanley meter the watts are given by the following formula:

$$\text{Meter watts} = \frac{100\,R\,K}{T} \qquad (2)$$

where only R = number of revolutions in T seconds;
T = time in seconds for R revolutions;
K = a constant marked on the meter case.

This formula applies also to the Fort Wayne induction meters, the values of K being given for different sizes of meters, in a table furnished by the manufacturers.

READING RECORDING WATTMETERS

73. The dials of most wattmeters record either watt-hours or kilowatt-hours. In some cases, as with the earlier types of Thomson meter, the reading taken from the meter dials must be multiplied by a constant in order to obtain the watt-hours. This constant is usually marked on the dial. However, the general practice now is to make the dials of meters direct reading except in the case of meters of large capacity. If no constant is marked on the dial it can be assumed that the meter is direct reading.

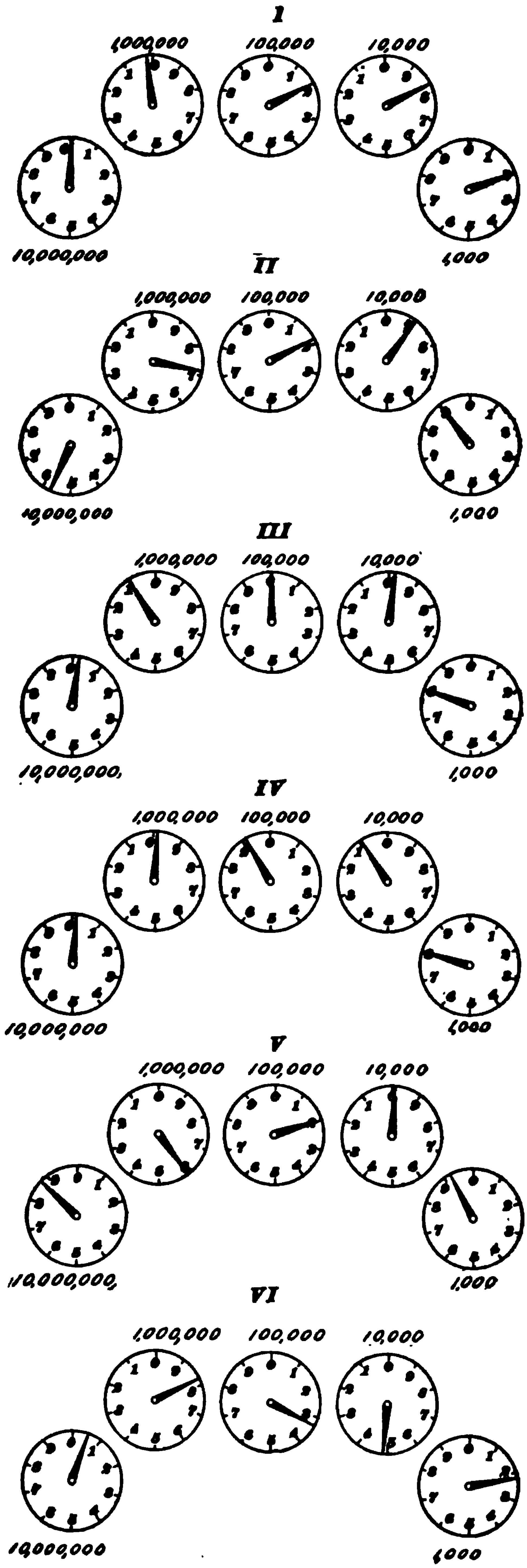

I
1,000,000
100,000
10,000
10,000,000
1,000
II
1,000,000
100,000
10,000
10,000,000
1,000
III
1,000,000
100,000
10,000
10,000,000
1,000
IV
1,000,000
100,000
10,000
10,000,000
1,000
V
1,000,000
100,000
10,000
10,000,000
1,000
VI
1,000,000
100,000
10,000
10,000,000
1,000

Fig. 70

74. Reading Thomson Meter.—The Thomson meter has five dials. The lowest reading pointer is the one to the extreme right (facing the meter); it is marked 1,000, which means that one complete revolution of the hand indicates 1,000 watt-hours, and that each division therefore represents 100 watt-hours. The next one to the left is 10,000 to a revolution, or 1,000 for a division, and so on. Fig. 70 shows six different readings, by studying which the student should be able to take readings from any meter.

Beginning at the left, number the pointers 1, 2, 3, 4, and 5. Then, in *I*, Fig. 70, pointer 5 is on *2* and is read 200. Pointer 4 is two-tenths of the way between *8* and *9* and is read 8,000. Pointer 3 is read 10,000. Pointer 2 has not gone through its first division; likewise pointer 1. The statement is then 18,200.

The statement of *II* is 5,718,900 (not 5,719,900, as it frequently would be read). Pointer 4 should not be read *9* until pointer 5 has completed its revolution and is again at *0*.

The statement of *III* is 99,800 (not 109,800), because the 100,000 mark will not be reached until pointer 5 has passed from *8* to *0*, when 4 and 3 will be at *0*, pointer 2 at *1*, and pointer 1 just past the zero mark.

The statement of *IV* is 9,990,800. Pointer 1 is slightly misplaced. Otherwise, the reasons given above will apply to this statement.

The statement of *V* is 8,619,900. Pointer 2 is misplaced. It should be two-tenths of the way between *6* and *7* instead of nearly over *6*, as shown.

The statement of *VI* is 834,200. Pointer 4 is misplaced. It should be two-tenths to the right of *4* instead of to the left of *5*. These misplaced hands are frequently met with in practice and are generally caused by a knock in removing the cover, or, perhaps, they are a little eccentric.

Rule.—*To ascertain the number of watt-hours that has been used by a consumer from one date to another, subtract the earlier statement from the latter and multiply by the constant of the meter, if one is marked on the dial. In case no constant is*

marked on the meter, the constant is 1, and the readings are taken as given by the dial.

Example.—An electric company supplies power to operate a motor for one of its customers. The rate charged is 5 cents per kilowatt-hour. The reading of the meter on January 30 is 8,619,900, and on February 28, it is 9,990,800. The constant of the meter is 2. What should be the amount of the bill for the month?

Solution.—The number of watt-hours supplied between Jan. 30 and Feb. 28 = (9,990,800 − 8,619,900) × 2 = 2,741,800.

2,741,800 watt-hours = 2,741.8 K. W.-hours, which at 5 cents per K. W.-hour would amount to 2,741.8 × .05 = $137.09. Ans.

SPECIAL METERS

75. The Two-Rate Meter.—Most electric-light stations have their period of heaviest load for a few hours only in the evening. During the daytime the plant is lightly loaded, and a large part of the machinery is standing idle. In order

Fig. 71

to obtain a *day load* and thus work the plant to best advantage, some companies supply power during the daytime at specially low rates in order to induce customers to use electric motors. For measuring the power supplied to such

customers, *two-rate meters* are sometimes used. A **two-rate meter** is one that records the power during certain hours of the day at a rate different from that at other hours. One of the earlier types made by the General Electric Company was a regular Thomson recording meter provided with two dials and recording trains, which were arranged so that a self-winding clock would throw either one or the other into gear with the meter shaft at the proper time. The energy recorded on the two dials was then charged for at different rates.

In the later type of General Electric two-rate meter an ordinary Thomson meter A, Fig. 71, with a single dial is used. Connected to the potential circuit of A is a self-winding clock mechanism contained in the case B. The case also contains a resistance, which, during certain hours, is inserted in series with the armature of the wattmeter, thus making the meter run at a reduced speed during those hours. The two-rate attachment, therefore, makes the meter run slow during certain hours, which is equivalent to charging for the power at a low rate during those hours.

76. Maximum-Demand Meter.—The maximum amount of current that the various customers consume determines in large measure the capacity of the station equipment. Some customers might use large currents for short intervals only, but the plant must be capable of handling these large currents; in some cases, therefore, the maximum demand for current is taken into account in making up the bill; for example, all current over a certain amount is charged for at a higher rate. One style of instrument used for indicating the maximum current used above a certain amount is the *Wright maximum-demand meter*, shown in Fig. 72. It consists of a **U**-shaped tube, hidden partly by the scale in the figure, which has bulbs A, B on either end; a branch tube C is attached near B and carried down over the scale. The lower end of tube C is closed. The current flows from D to E through the resistance strip F coiled around bulb A. The tube is partially filled with liquid, which remains in it as long

as the current does not exceed a certain amount. If, however, the current exceeds the allowable amount, the expansion of the air in A due to the heating of strip F will force liquid into the tube C. Any increase in the current will force

Fig. 72

over more liquid, and from the height of the column of liquid in tube C the charge can be estimated. The U-shaped tube is mounted on an arm that can be swung up after the reading has been taken, thus emptying tube C into the U-shaped tube.

INDEX

NOTE.—All items in this index refer first to the section and then to the page of the section. Thus, "Bus-bars 25 19" means that bus-bars will be found on page 19 of section 25.

T